TECHNICAL REPORT M-70-14

PENETRATION RESISTANCE OF SOILS

Report 1

TESTS WITH CIRCULAR FOOTINGS IN AIR-DRY SANDS

by

A. J. Green

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Sponsored by Assistant Secretary of the Army (R&D), Department of the Army

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

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ARMY-MRC VICKSBURG, MISS.

FOREWORD

The study reported herein was conducted during the period 1966-1969 and was funded by Project 4A013001A91D, "In-House Laboratory Initiated Research Program" Item S, sponsored by the Assistant Secretary of the Army (R&D).

The project was directed by Mr. A. J. Green, Research Projects Group, Mobility Research Branch (MRB), Mobility and Environmental (M&E) Division, at the U. S. Army Engineer Waterways Experiment Station (WES). The test program was carried out by personnel of the MRB under the general supervision of Mr. W. J. Turnbull, former Technical Assistant for Soils and Environmental Engineering, and Messrs. W. G. Shockley and S. J. Knight, Chief and Assistant Chief, M&E Division; and under the direct supervision of Dr. D. R. Freitag, former Chief, MRB, and now Chief, Office of Technical Programs and Plans, WES. The report was prepared by Mr. Green.

COL John R. Oswalt, Jr., CE, COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE, were Directors of WES during this study. Messrs. J. B. Tiffany and F. R. Brown were Technical Directors.

CONTENTS

NOTATION

a	Constant of proportionality
A	Area of footing
b	Length of footing
c	Soil cohesion
d	Width or diameter of a footing
d_c, d_q, d_γ	Depth factors
D_r	Soil relative density
F	Force on footing
F_p	Vertical force on cylinder base
F_s	Vertical force along cylinder sidewalls
F_t	Total vertical force on cylinder
g	Gravity
G	Penetration resistance gradient
i_c, i_q, i_γ	Inclination factors
K	Coefficient of earth pressure
ℓ	Significant linear dimension of footing
N_c, N_q, N_γ	Primary bearing capacity factors
$N_{q\gamma}$	Combined bearing capacity factor
P, q	Unit pressure; mean pressure
P_s	Cylinder sidewall friction per unit area
q_f	Unit vertical bearing capacity
s	Circumference of footing
s_c, s_q, s_γ	Shape factors
v	Rate of loading
z	Sinkage
β	Viscosity
γ	Density (unit weight of soil)
ϕ	Soil friction angle

CONVERSION FACTORS, METRIC TO BRITISH AND BRITISH TO METRIC UNITS OF MEASUREMENT

Metric units of measurement used in this report can be converted to British units as follows:

Multiply	By	To Obtain
millimeters	3.937	inches
centimeters	0.3937	inches
meters	3.2808	feet
newtons	0.225	pounds
kilonewtons per square meter	0.1450	pounds per square inch
kilonewtons per cubic meter	271.4472	pounds per cubic inch

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
pounds per square inch	6.895	kilonewtons per square meter
pounds per cubic foot	0.01602	grams per cubic centimeter

SUMMARY

The study reported herein is an analysis of the penetration of circular plates and smooth-walled and rough-walled cylinders in two sands, each prepared at three strength levels. The penetration elements ranged from 2.5 to 61 cm in diameter, and the speed of penetration in all tests was 2.5 mm/sec.

No basic differences were found in the shape of the penetration resistance curves for plates and cylinders, and the forces on the base of the cylinders were only slightly higher than those on the plates. The forces due to friction on the sidewalls of the cylinders were greater for the rough-walled cylinders than for the smooth, as could be expected, but they did not vary systematically with sand density in either case.

Collapse of the data into a single function for sand was achieved by plotting a dimensionless pressure parameter $P/\gamma d$ versus a penetration parameter z/d. This gave evidence that pressure-sinkage relations, and thus bearing capacity, of large footings can be predicted from model tests. Dimensionless scaling relations and theoretical equations that include a friction angle term were also found to predict bearing capacity, but the problems in measuring a true friction angle make the use of these relations questionable for this purpose. The tests were deemed successful and eliminated irregularities encountered in the results of routine tests. The data should also be of great value in investigations of depth factors for bearing capacity of sand. This report will be supplemented by a report on similar tests in clay.

PENETRATION RESISTANCE OF SOILS

TESTS WITH CIRCULAR FOOTINGS IN AIR-DRY SANDS

PART I: INTRODUCTION

Background

1. Bearing capacity of soils has been one of the principal topics of discussion in the field of soil mechanics for several decades. In the last few years, many papers have been written on the subject, and a number of theories or postulations have been offered. Many of these represent attempts to add to the basic relations such items as slope, depth, roughness, and placement mode factors (e.g. driven versus poured-in-place piles).[1-6] A close agreement between theoretical prediction and test results in cohesionless soils seldom has been obtained, as was pointed out by Hvorslev.[7] The reasons given for this vary from author to author. Some of the reasons are as follows:

- a. Improper placement of the sand, resulting in test specimens that were layered or tended to increase or decrease in density with depth.
- b. Lack of reliable measurement of a density-depth profile.
- c. Boundary effects in test bins that were too shallow, too narrow, or too small in diameter.
- d. Failure to recognize the existence of the small amount of effective cohesion exhibited by some sands.
- e. Inaccurate determination of the internal friction of the soil (e.g. curved Mohr envelopes and shell effects in triaxial specimens).

2. Depth and other factors given by some authors were obtained through empirical or quasi-empirical means and, in some cases, were based on a relatively small number of tests in a single sand. Thus, they may be questioned on the basis of reasoning similar to that given above. It was recommended during a mobility consultants' conference at the U. S. Army Engineer Waterways Experiment Station (WES) that penetration tests be performed in uniform sand and clay, using systematic variation in the diameter

of the footings. The results should be useful in both mobility and basic bearing capacity problems.

3. Not all of the variables were studied in the program reported herein. However, for the tests that were made, every effort was made to avoid the pitfalls of testing that generally have obscured the reliability of penetration test results. Equipment was fabricated to facilitate proper placement of the sand and to enable an accurate determination of the in situ density-depth relation after each specimen was constructed. Test bins of ample width and depth were provided, and consideration was given to the possible presence of cohesion in the sands tested and to the accurate determination of the internal friction of the test soils.

Purpose and Scope

4. The principal objective of this program was to establish scaling relations for families of plates and cylinders. To realize this objective, the effects of density, relative density, friction angle, and sand type (grain size and shape) on penetration resistance were determined. In addition the variations in penetration resistance that resulted from varying the roughness and depth of penetration of the footings were investigated.

5. Two air-dry sands were used in the program, and three series of tests were conducted in each. The model footings, ranging from 2.54 to 60.96 cm* (1 to 24 in.) in diameter, were circular plates and smooth- and rough-walled cylinders; the bases of all footings were rough. The cylinders were used to eliminate the inward flow of sand which occurs over the plates.

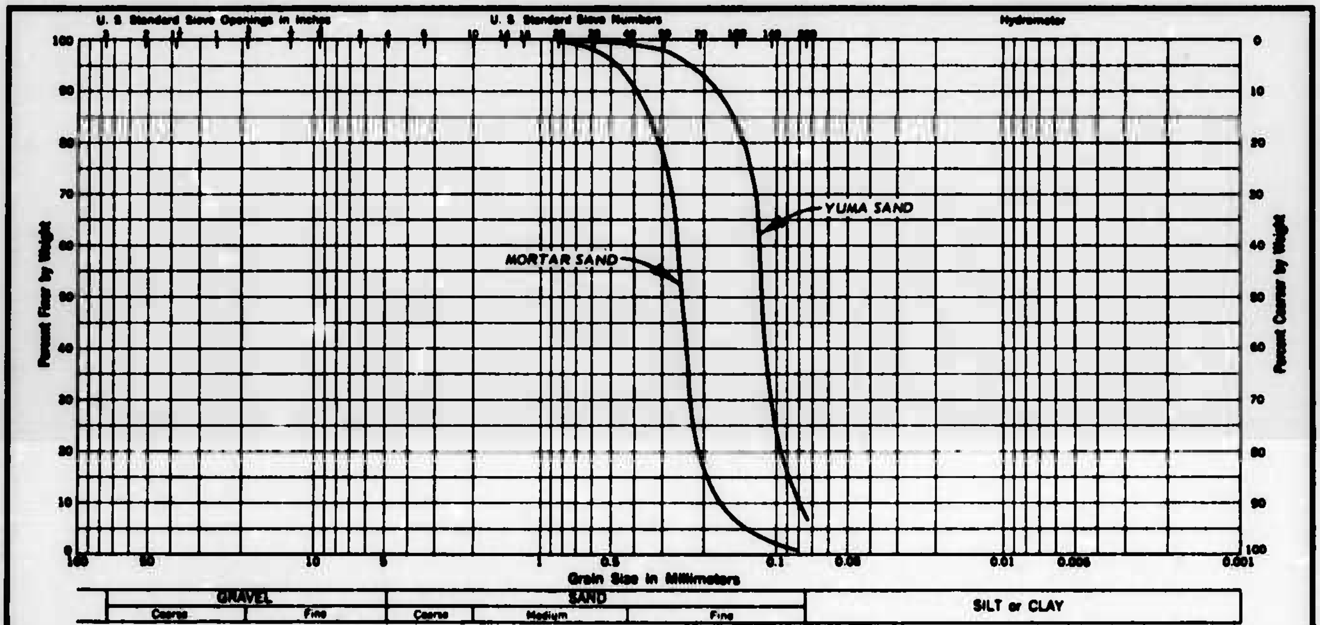
6. This report contains an explanation of the functions of the equipment used, an analysis of results obtained, and a comparison of these results with results computed from existing bearing capacity relations. It will be supplemented by a report of similar tests in clay.

* A table of factors for converting metric to British and British to metric units of measurement is presented on page ix.

PART II: SOILS, EQUIPMENT, AND TEST PROGRAM

Test Soils

7. The two sands utilized in this study were tested in the air-dry state. One was a washed sand from an alluvial plain in the Big Black River basin near Vicksburg, Mississippi (mortar sand), and the other was a dune sand from near Yuma, Arizona (Yuma sand). Gradation and classification data are presented in fig. 1.



Number	Depth	Natural Moisture	L.L.	P.L.	P.I.	Classification	MAX DENSITY	MIN DENSITY
						MORTAR SAND (SP)	106.1	87.4
						YUMA SAND (SP-SM)	104.0	87.0

Fig. 1. Soil gradation and classification data (densities are in pounds per cubic foot)

Equipment

Soil bins

8. The soil bins (fig. 2) are approximately 3.54 m wide, 1.68 m deep, and 51.82 m long. At one end of the second lane shown in fig. 2, a 12.19-m-long portion is 2.13 m deep. Tests with large penetration elements

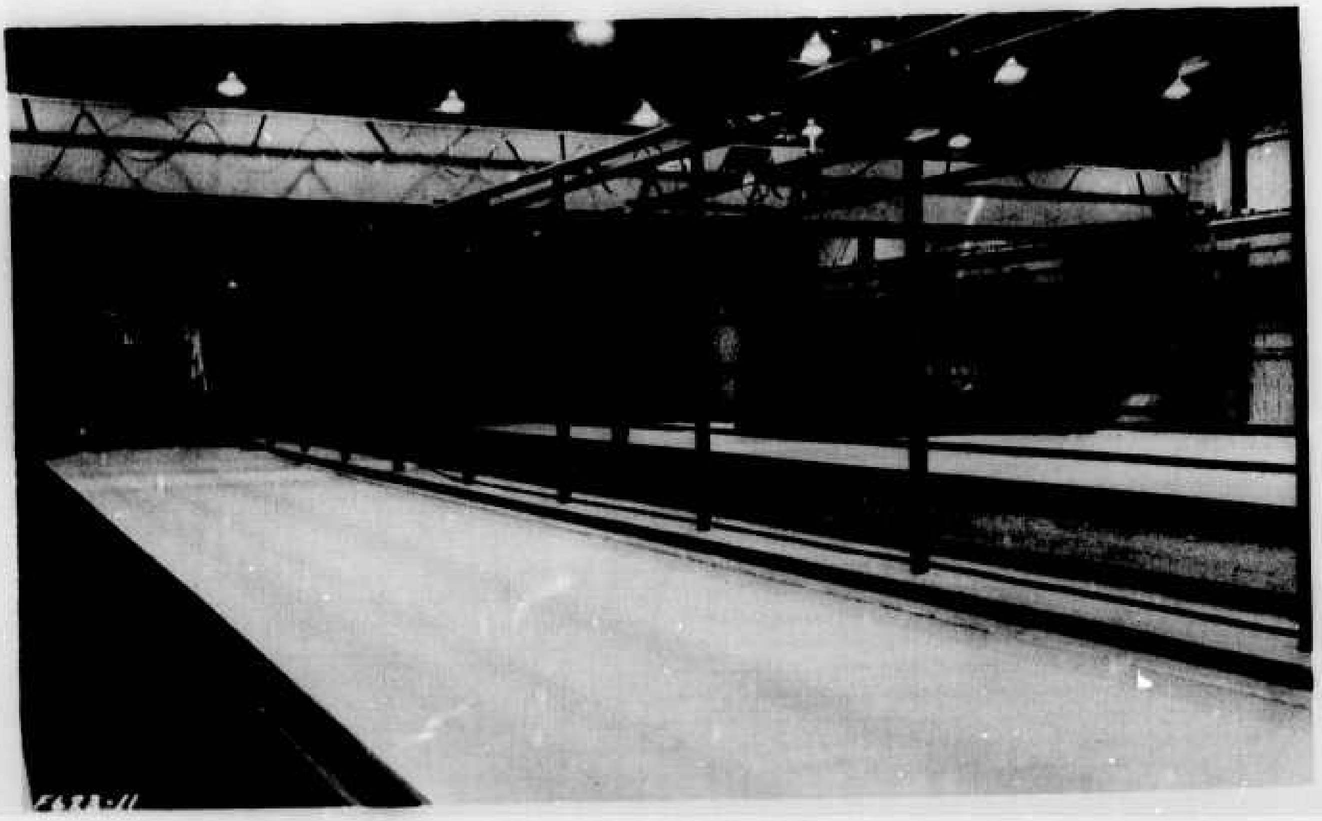


Fig. 2. Soil bins

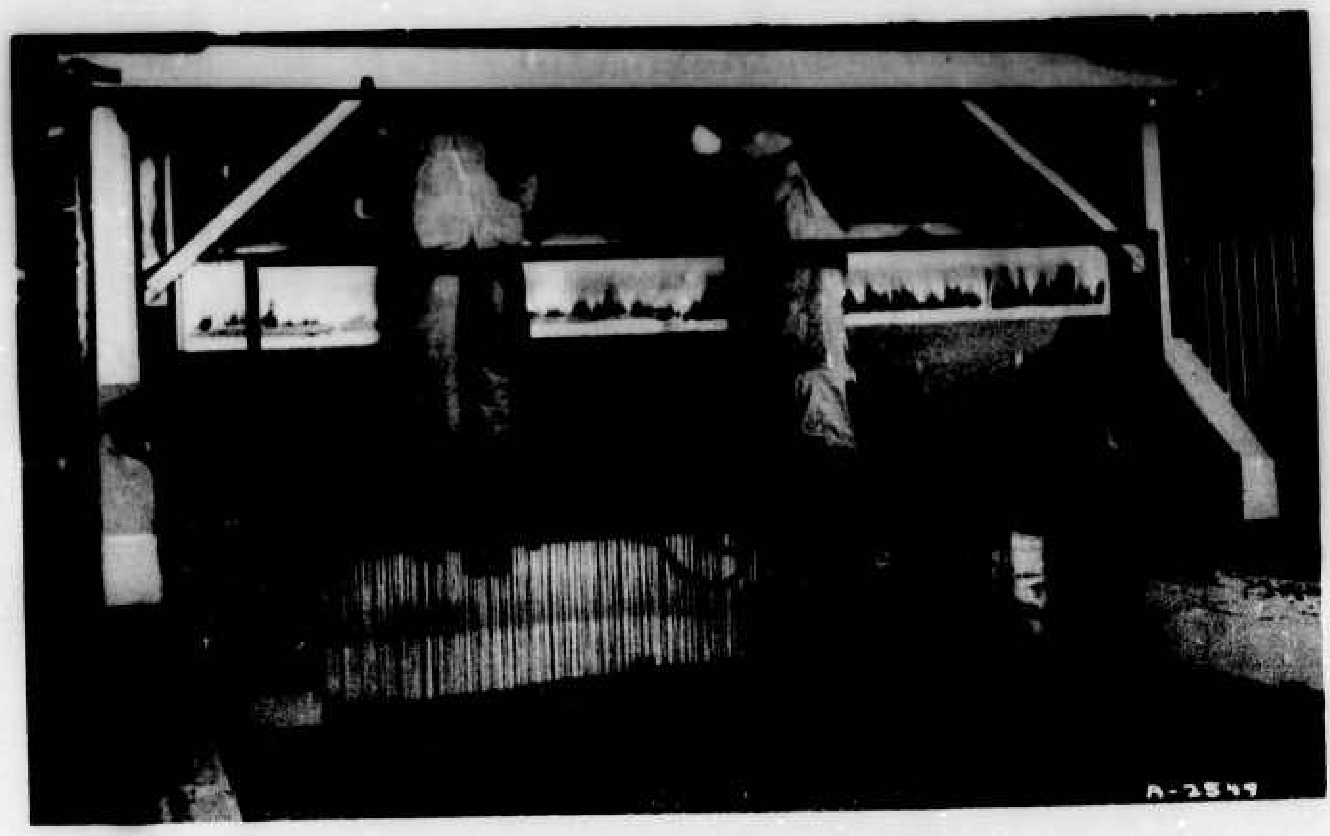


Fig. 3. Sand spreader in use

were made in this area whenever possible.

Sand spreader

9. Sand was placed in the bins with a spreader (fig. 3) designed so that the height of fall and rate of flow of the sand could be controlled. The density of the sand could be increased as the height of sand fall was increased and as the rate of sand flow was decreased. The effectiveness of this apparatus is discussed in paragraphs 33-34. To achieve a high relative density (80 to 90 percent) in the Yuma sand (series 7), it was necessary to compact the test section. The sand was placed in the bins in 15-cm layers, and each layer was trafficked with a pneumatic-tired roller (fig. 4) until the required density was achieved for that layer.

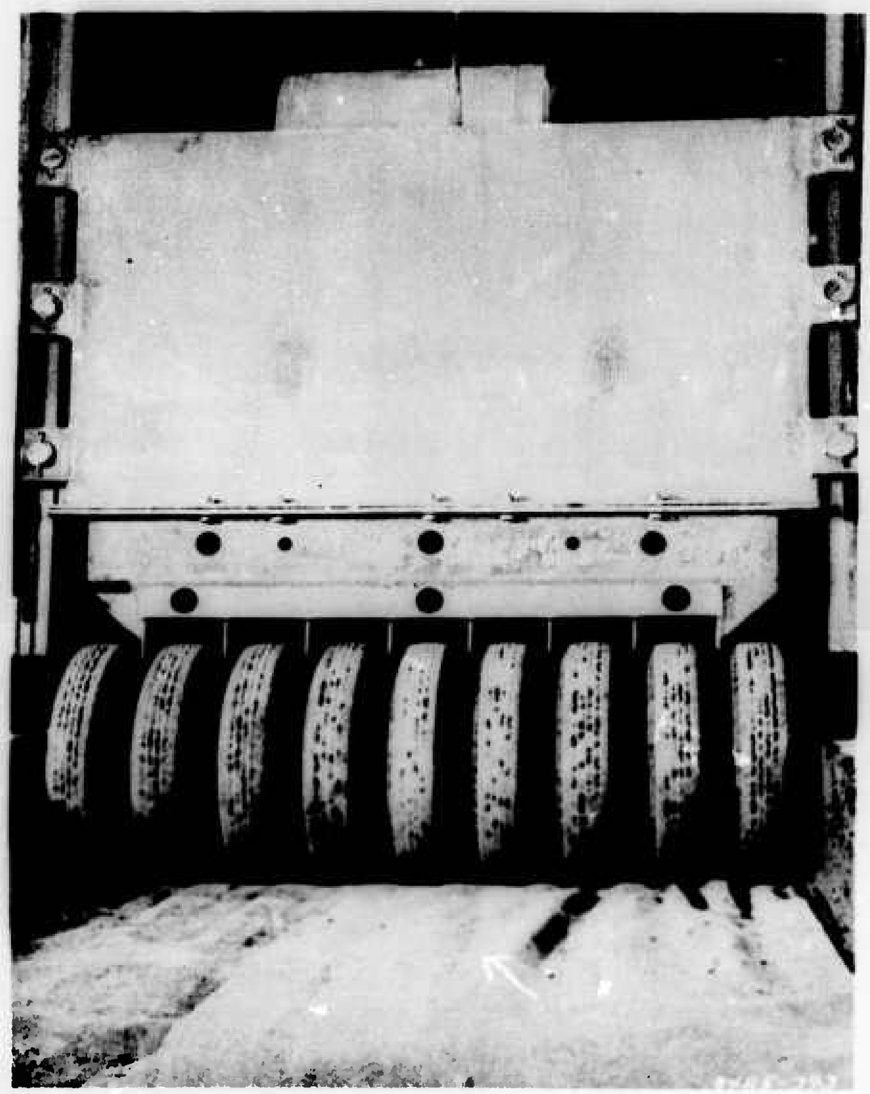
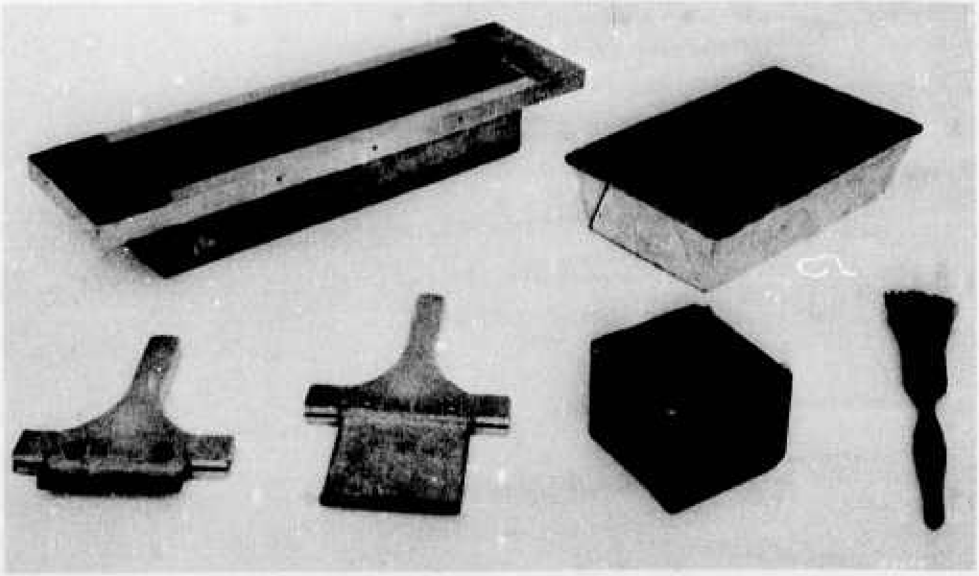


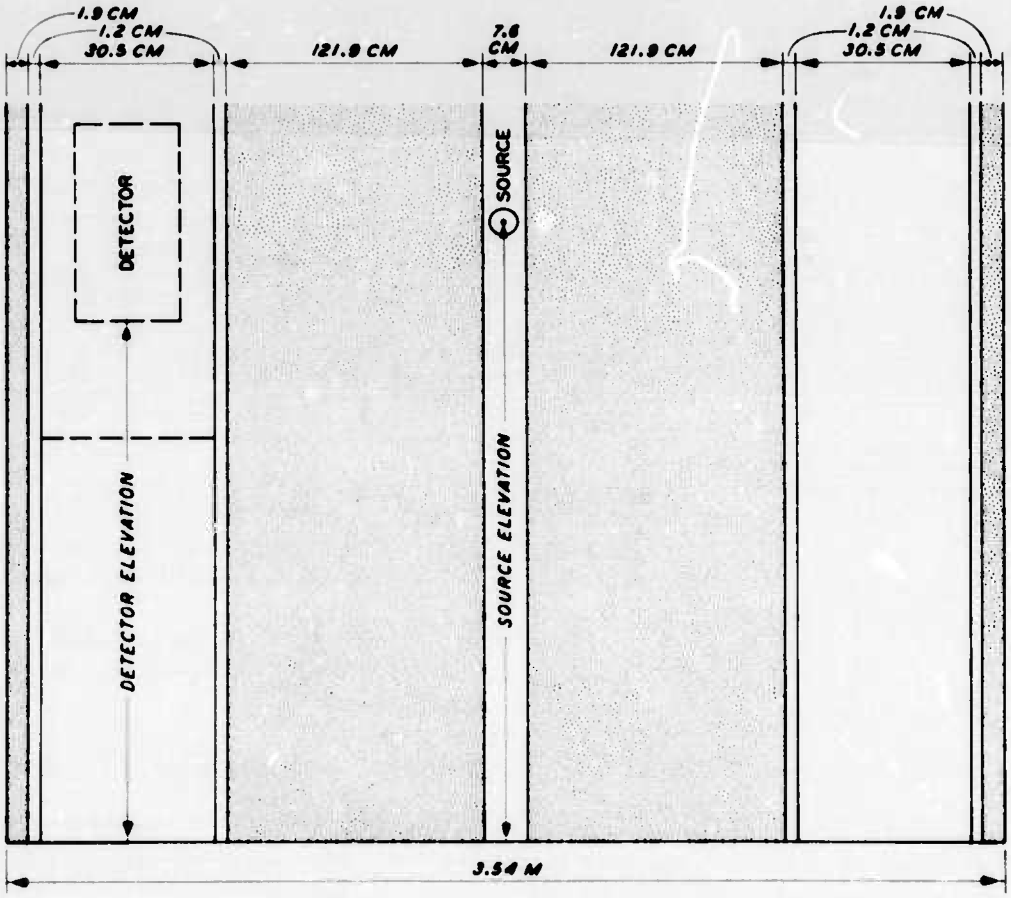
Fig. 4. Pneumatic-tired roller used for compacting test sections

Density-measuring devices

10. Gravimetric. The apparatus shown in fig. 5a was used to measure the in situ density of the top 5 cm of soil at selected elevations as the section was prepared. The steel box shown was carefully forced into the material, and the material was removed (using the scoops shown in fig. 5a) and weighed. Since the volume of the box was known, the weight per unit volume of the excavated material could be computed.



a. Gravimetric density-measuring apparatus



b. Test sample cross section with access tubes of nuclear density-measuring device in place

Fig. 5. Density measurement systems

11. <u>Nuclear.</u> Since a nonmechanical device was desired to obtain an in situ depth-density profile after the sample had been prepared, a direct transmission "nuclear density device" was used. The placement of access tubes in the sand test sections is shown in fig. 5b. These tubes were made in 15-cm sections so that they would not interfere with the sand-placing operation when a low height of fall was desirable. Sections were added as the depth of the sand was increased. The reading at a particular point was assumed to reflect the average density of a specimen with a major axis of approximately 122 cm and a minor axis of 7-10 cm. Additional details regarding this equipment are furnished in the second report in this series.[8]

<u>Loading apparatus</u>

12. The apparatus (fig. 6) used to push the penetration elements into the soil mass is capable of producing a vertical thrust of 448 kN at speeds up to 3.33 mm/sec. Speed of penetration during this test program was 2.5 mm/sec. The ram is powered by a shock-mounted hydraulic pump system. Prior to a testing cycle, the surface of the entire test section was carefully leveled, and a penetration began with the plate or cylinder slightly above the surface of the soil so that the ram had achieved a speed of 2.5 mm/sec before it made contact.

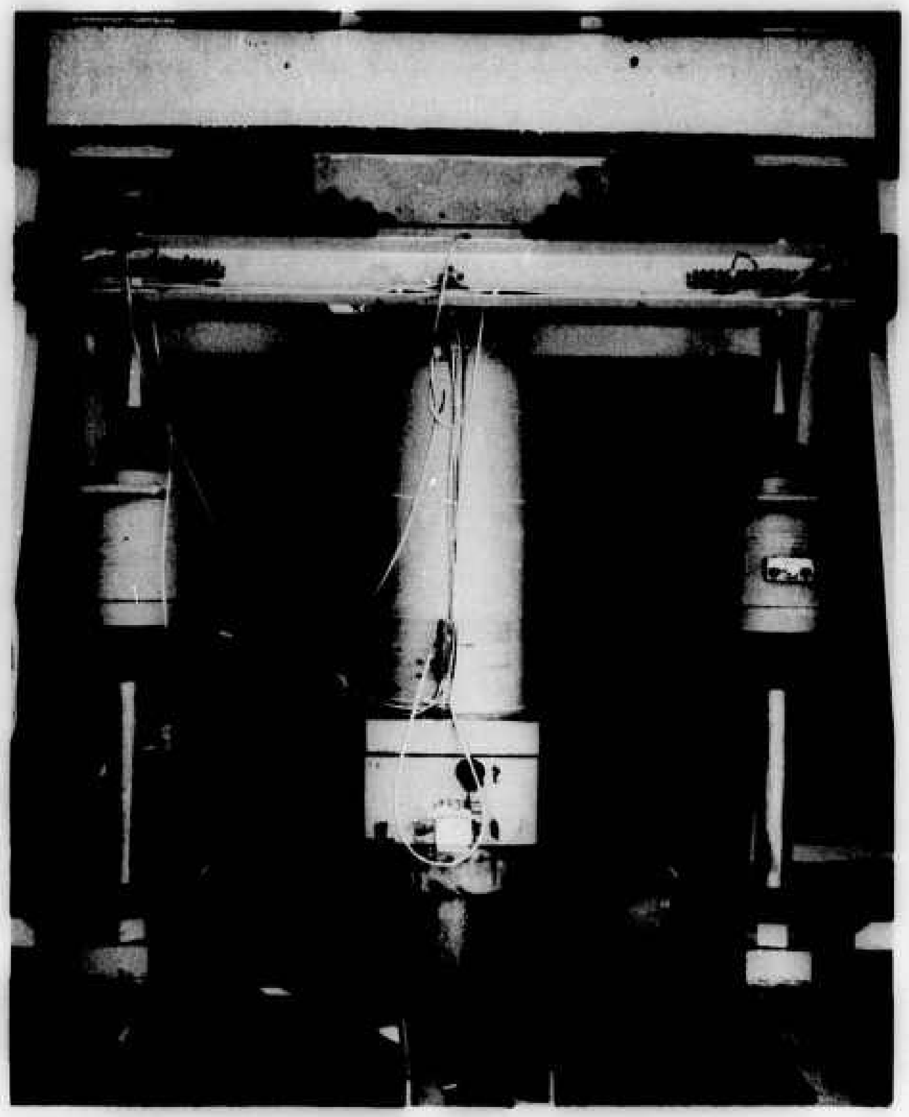


Fig. 6. Loading apparatus

The hydraulic pump supplied sufficient pressure to maintain a constant speed during the penetration, and the test was stopped when the desired depth was reached.

Model footings

13. The diameters of the plates were 2.54, 5.08, 10.16, 20.32, 30.48, 40.64, and 60.96 cm; those of the cylinders were the same, except no 2.54-cm-diam cylinders were tested. Not all footings were used in each test series, as shown in table 1 and the tabulation in paragraph 17. The plates and the bases of the cylinders were designed so that bending would be minimized. For example, the base of the 60.96-cm cylinder was a solid steel plate approximately 23 cm thick. Relatively thin plates, when used, were reinforced with vertical webs as appropriate.

14. The bases of all footings were roughened by gluing sand to them. The sides of the cylinders were roughened in the same manner; however, the sand could be removed easily with a solvent when tests with smooth-walled cylinders were required.

15. The original cylinder design provided for a separate measure of the vertical force along the sidewalls F_s and the total vertical force on the cylinder F_t. However, the portion of the cylinder intended to provide a measure of F_s (the four pairs of strain gages spaced 90 deg in fig. 7) gave erratic results, probably because during handling the strain-sensitive elements were damaged by excessive displacement. Therefore, the instrumentation system was altered so that the vertical force on the base of the cylinder F_p (the two pairs of strain gages spaced 180 deg in fig. 7) and F_t were recorded. In the base of one 20.32-cm-diam

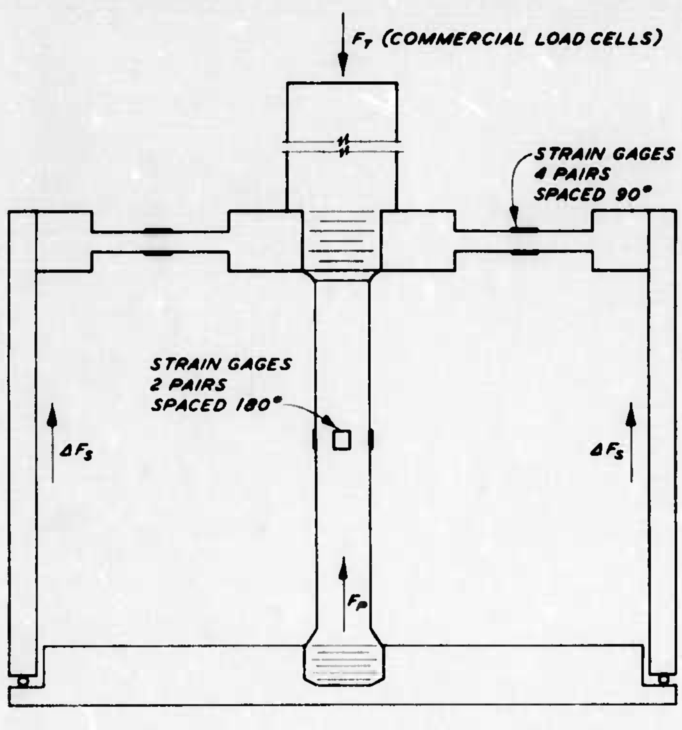


Fig. 7. Schematic of instrumented cylinders

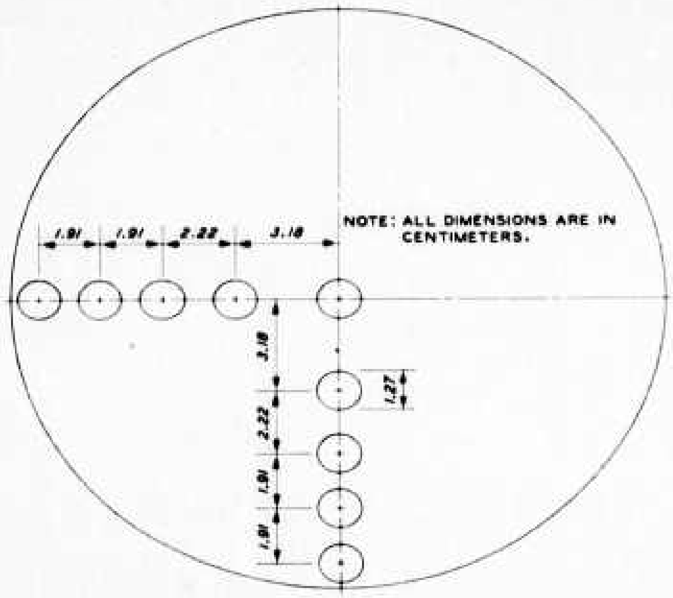


Fig. 8. Pressure transducers in 20.32-cm-diam plate (covered with membrane during test)

cylinder, nine deflecting diaphragm-type transducers were mounted (fig. 8) to obtain a measure of the distribution of forces at the soil-footing interface.

Recording equipment

16. Forces and displacements obtained during the tests were recorded on an analog magnetic tape and an x-y recorder.

Test Program

17. As previously mentioned, three series of tests were conducted in each of two sands with plates and smooth-walled and rough-walled cylinders ranging from 2.54 to 60.96 cm in diameter, but the entire range of footings was not used in each test series. In the first two series, a few of the cylinders were instrumented to obtain a measure of the vertical component of the forces on the sidewalls. Examination of these early data indicated a need to instrument as many of the cylinders as practical to obtain this measurement. Series 3, the first series in mortar sand, did not include tests with plates. The complete test program is outlined on the following page.

Sand Type	Test Series	Density (Unit Weight) kN/m^3	Relative Density %	Footings, cm Diam 2.54	5.08	10.16	20.32	30.48	40.64	60.96
				Plates						
Yuma	1	14.14	20	--	X	X	X	X	X	--
	2	14.93	52	X	X	X	X	X	--	--
	7	15.87	85	--	X	X	X	X	--	--
Mortar	3	15.05	55	--	--	--	--	--	--	--
	5	16.40	92	--	X	X	X	X	--	--
	6	14.72	34	--	X	X	X	X	--	--
				Smooth-Walled Cylinders						
Yuma	1	14.14	20	--	--	X	X	X	X	--
	2	14.93	52	--	--	X	X	X	--	--
	7	15.87	85	--	X	X	X	X	X	X
Mortar	3	15.05	55	--	X	X	X	X	X	X
	5	16.40	92	--	X	X	X	X	X	X
	6	14.72	34	--	X	X	X	X	X	X
				Rough-Walled Cylinders						
Yuma	1	14.14	20	--	--	X	--	X	--	--
	2	14.93	52	--	--	X	--	X	--	--
	7	15.87	85	--	X	X	X	X	X	--
Mortar	3	15.05	55	--	X	X	X	X	X	X
	5	16.40	92	--	X	X	X	X	X	--
	6	14.72	34	--	X	X	X	X	X	--

PART III: BEARING CAPACITY RELATIONS

18. The classical bearing capacity relation as given by Terzaghi in 1943[9] is:

$$q_f = cN_c + N_q + \frac{1}{2} \gamma dN_\gamma \tag{1}$$

where

q_f = unit vertical bearing capacity
c = soil cohesion
N_c, N_q, N_γ = primary bearing capacity factors
γ = soil density
d = width or diameter of footing

The bearing capacity factors in this relation were derived from considerations of uniform, normal loading of a long, rectangular area. When different shapes, depths of burial, and nonuniform or inclined loads are involved, the basic relation must be modified.

19. Meyerhof[6] and Brinch Hansen[1] prepared the following relation:

$$q_f = cN_c s_c d_c i_c + qN_q s_q d_q i_q + \frac{1}{2} \gamma dN_\gamma s_\gamma d_\gamma i_\gamma \tag{2}$$

where

s_c, s_q, s_γ = shape factors
d_c, d_q, d_γ = depth factors
i_c, i_q, i_γ = inclination factors

This form represents an attempt to include shape, depth, and inclination factors. Several of these factors in equation 2 were empirically determined. Other researchers (De Beer and Ladanyi)[10] have suggested the inclusion of such factors, but do not concur with the general form of the relation given by Meyerhof and Brinch Hansen. Meyerhof suggested a variable friction angle, with the variations being a function of footing shape and the associated changes in stress condition. Kishida[11] developed a formula for accounting for changes in the friction angle during shear.

20. Meyerhof and Brinch Hansen are in essential agreement as to the general method of including shape, depth, and inclination factors. However, the specific relations derived by Brinch Hansen are different from those

first derived by Meyerhof. More recently Meyerhof has described a set of relations similar to those of Brinch Hansen. Nevertheless, it is believed instructive to examine both general types of relations. This is done below.

Meyerhof's Equation

21. Meyerhof's assumed rupture patterns (fig. 9) are somewhat different from the classical patterns given by Terzaghi. For cohesionless

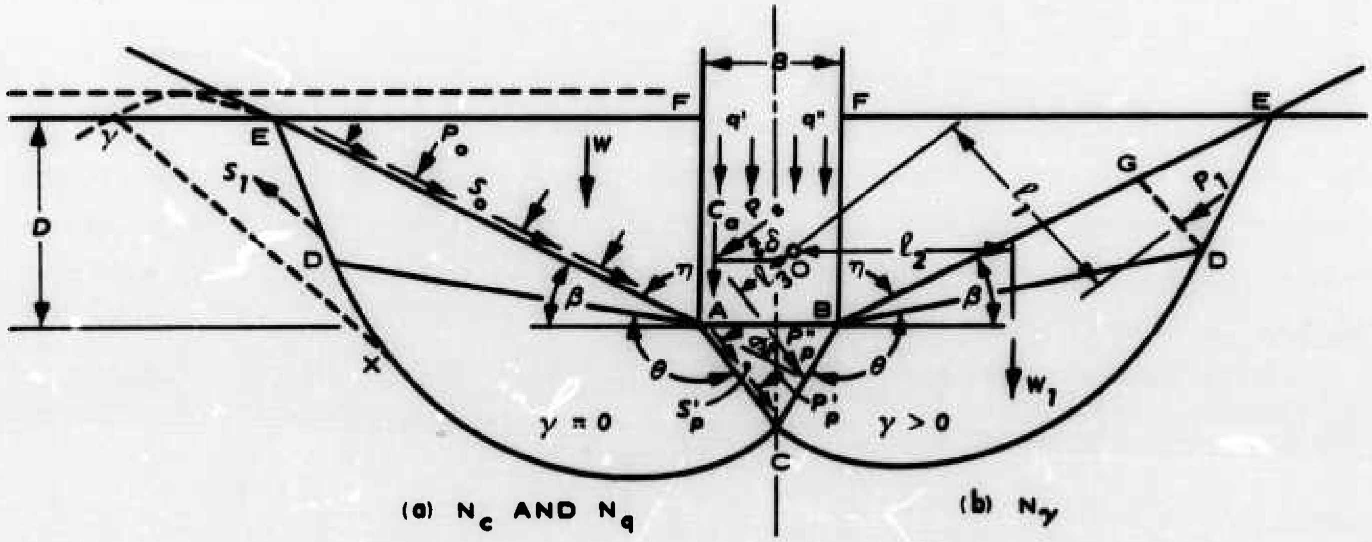


Fig. 9. Determination of general bearing capacity factors for strip foundation with rough base (after Meyerhof[4])

soils, the general equation for the mean pressure q beneath a footing is given as

$$q = \frac{1}{2}\gamma d s_\gamma N_{q\gamma}$$

or

$$\frac{q}{\gamma d} = \frac{s_\gamma N_{q\gamma}}{2} \qquad (3)$$

where

γ = unit weight of the soil

d = width or diameter of the footing

s_γ = shape factor to be applied on other than infinitely long strip foundations

$N_{q\gamma}$ = combined bearing capacity factor accounting for the classical N_q and N_γ values of bearing capacity theories

22. Meyerhof gives a separate set of shape factors for circular footings. These factors vary with the penetration parameter z/d, the friction angle, and the type of placement (i.e. buried or driven). The bearing capacity factor $N_{q\gamma}$ is related to the bearing capacity factors N_q and N_γ; but other factors are involved in the computation, so that $N_{q\gamma}$ is a function of: (a) width (or diameter) of the footing, (b) unit weight of the soil, (c) angle of internal friction of the soil, (d) coefficient of earth pressure at rest, (e) sidewall friction acting on the footing (smooth or rough), and (f) depth of footing. The net result is that instead of there being a solution only for circular footings in a cohesionless soil of a specific consistency, solutions also can be obtained for buried or driven footings with smooth or rough sidewalls. Each of these four basic solutions varies as the assumed earth pressure coefficient for a given soil consistency. Solutions were derived (fig. 10) for rough-walled, buried, cylindrical footings at two soil consistencies (friction angle = 35° and 38°)

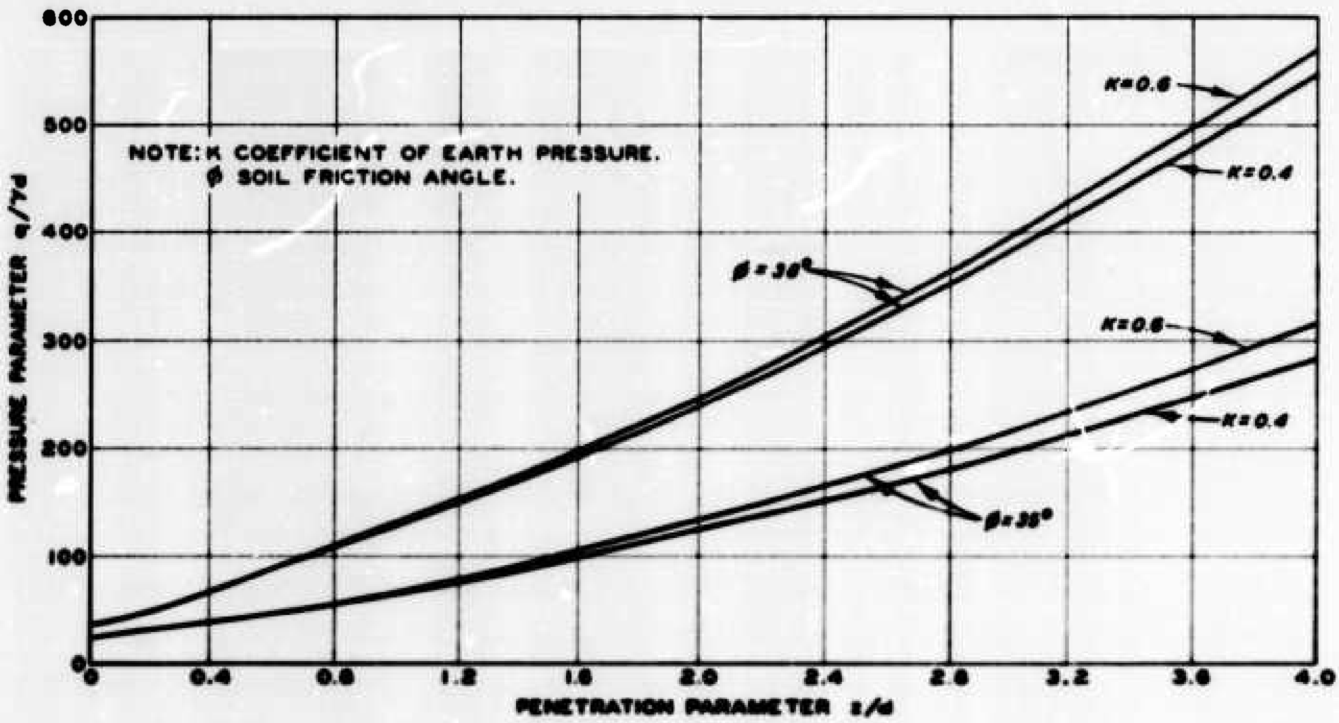


Fig. 10. Meyerhof's equation for buried cylinders with rough sidewalls in cohesionless soils

and two earth pressure coefficients (0.4 and 0.6).

23. This combination of assumptions (i.e. rough-walled and buried) represents the highest obtainable set of values for the pressure parameter $q/\gamma d$ at a particular set of values of the friction angle and earth pressure coefficient. These values correspond very well with the solution of Brinch Hansen's equation (equation 4 below). The lowest values that can be obtained by varying the assumptions used in solving the Meyerhof equation are approximately 35 percent lower than those shown in fig. 10. The major part of this difference (≈25 percent) is due to the difference in the placement factor (i.e. the values for driven footings are ≈25 percent lower than for the buried ones when the other assumptions are held constant).

Brinch Hansen's Equation

24. Brinch Hansen's work, starting from a more classical point of view, uses each of the three classical bearing capacity factors-- N_c , N_q , and N_γ --and adds empirically determined shape, depth, and inclination factors. For cohesionless soils and vertically loaded circular elements, his equation reads:[1]

$$\frac{q}{\gamma d} = \frac{1}{2} N_\gamma s_\gamma d_\gamma + \frac{z}{d} N_q s_q d_q \tag{4}$$

The $q/\gamma d$ values are graphically represented in fig. 11 as functions of the penetration parameter z/d . The N_q and N_γ values were obtained from fig. 1 of reference 1. The shape and depth factors also are given in reference 1.

Comparison of Meyerhof and Brinch Hansen Equations

25. These equations cannot by any means be called exact ones, not even with the assumption of a perfectly plastic behavior of the soil. While this is obvious for Brinch Hansen's equation from its very development, it is true also for the equations of Meyerhof, where the concepts of the equivalent free surface and the assumption of uniform stresses

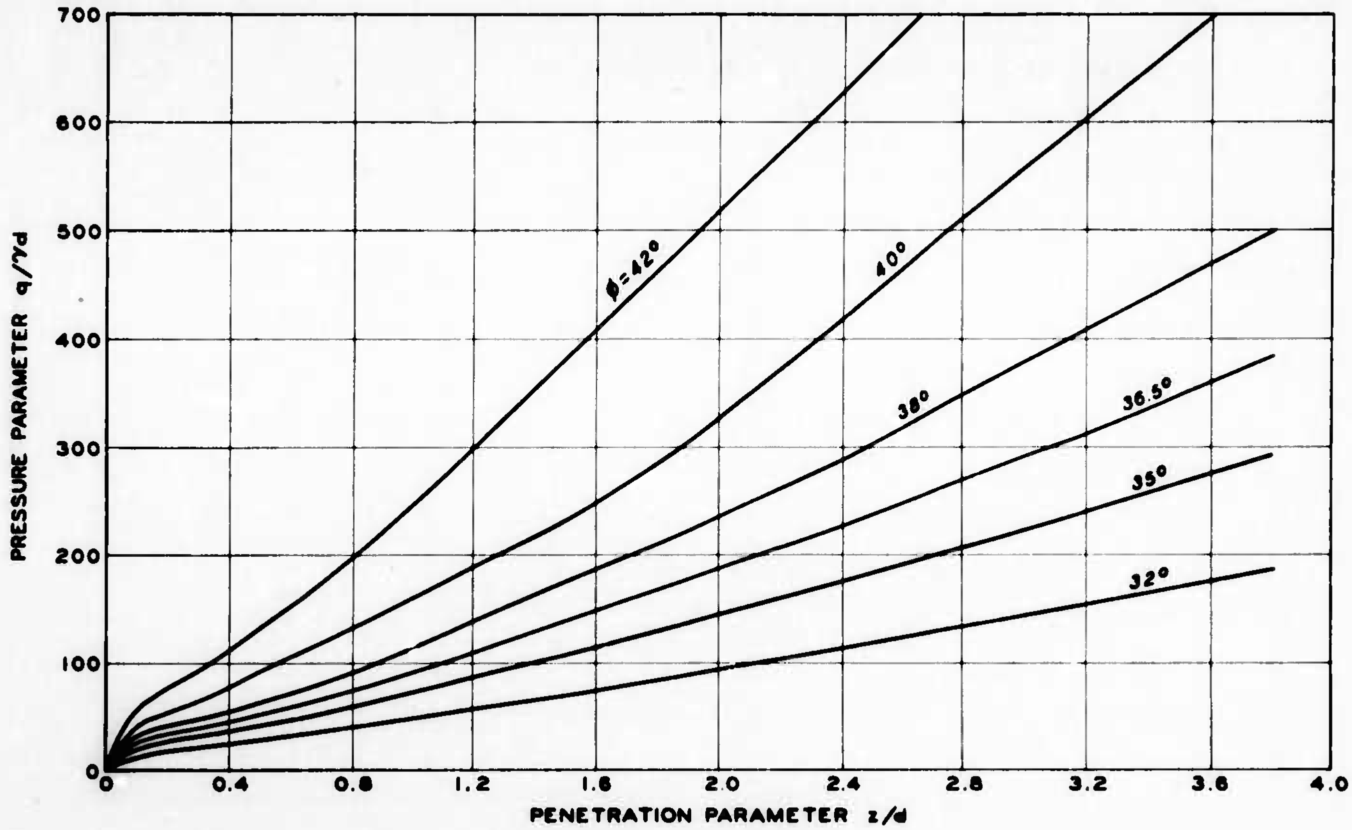


Fig. 11. Brinch Hansen's equation for vertically loaded circular footings in cohesionless soils

along that surface have not been validated. The shape factors in both equations 3 and 4 were empirically developed. Brinch Hansen does not consider variation of his solution with changes in the type of placement, roughness, and earth pressure coefficient. Therefore, to check values computed from these equations against the results of carefully conducted tests seemed important. That the equations deal only with the force on the base of the penetrating plates surmounted by cylinders must be emphasized.

Dimensionless Equations

26. An attempt to establish appropriate scaling relations for forces and displacements based on significant system parameters was deemed feasible. The variables considered in the formulation of this program and in the analysis were:

Variable	Symbol	Dimension*
Significant linear footing dimension	ℓ	L
Footing width or diameter	d	L
Footing length	b	L
Footing area	A	L^2
Footing circumference	s	L
Footing penetration (sinkage)	z	L
Force on footings	F	F
Unit pressure on footing	P , q	FL^{-2}
Soil cohesion	c	FL^{-2}
Soil friction angle	ϕ	Dimensionless
Soil consistency	γ , G	FL^{-3}
Soil relative density	D_r	Dimensionless
Rate of loading	v	LT^{-1}
Gravity	g	LT^{-2}
Viscosity	β	FTL^{-2}

* The following dimensional notation is used in this report: L--length, F--force, and T--time.

27. Since the rate of loading v was relatively slow (2.5 mm/sec), it seemed reasonable to disregard any viscous or inertial effects in this analysis. When these effects are ignored, the following functional relations can be written for circular penetration elements:

a. For cohesionless soils:

$$F/\gamma\ell^3 \text{ or } P/\gamma\ell = f(z/\ell , \phi) \tag{5}$$

b. For cohesive soils:

$$F/c\ell^2 \text{ or } P/c = f(z/\ell, \gamma\ell/c) \tag{6}$$

28. A number of authors suggest the addition of a shape factor on the right-hand side of the functional relations. In this program, only circular penetration elements were used, so this factor could not be evaluated.

29. Although the significant linear dimension term ℓ appears on both sides in each relation, the same physical footing dimensions need not be used on both sides of a given relation. For instance, the penetration parameter, z/ℓ , can be represented by any of the following:

$$z/\sqrt{A},\ z/b,\ z/d,\ z/s,\ z/\sqrt{sd},\ z/\sqrt{sb}$$

Again, since only circular footings were used in this program, the adequacy of forms intended to account for variations in shape (i.e. $z/\sqrt{A}$, z/s, $z/\sqrt{sd}$, $z/\sqrt{sb}$) could not be assessed. For convenience, the form z/d was used for this analysis.

30. The force parameter $F/\gamma\ell^3$ and the pressure parameter $P/\gamma\ell$ for cohesionless soils differ only by a constant when a single shape of footing is considered. To facilitate comparison of the test results with values derived from existing bearing capacity equations, the form $P/\gamma d$ was selected.

31. These selections having been made, the functional relation for cohesionless soils becomes:

$$P/\gamma d = f(z/d, \phi) \tag{7}$$

PART IV: TEST RESULTS

Evaluation of Strength-Density Profiles

32. One problem in conducting and analyzing bearing capacity tests in cohesionless soils is the preparation and description of soil conditions. Heretofore, it has been customary to assume that the prepared soil section will not vary in density with depth when the soil is sprinkled into the test pit from a constant height and at a constant rate of flow. Other experimenters have assumed that a uniform in situ strength increase with depth, as measured by a cone penetrometer or similar instrument, is an indication that density does not change with depth.

33. In this program an effort was made to place the soil in such a manner as to produce the desired density and to minimize variation in density with depth. Thus, the proper design and use of a sand-sprinkling system (fig. 3) capable of handling large quantities of sand was of primary importance. To assess the effectiveness of this system, in situ density was measured with gravimetric and nuclear devices both during and after the construction of the test sections. These measurements were accompanied by cone penetration tests. Results of cone penetration tests and density measurements in Yuma sand at relative densities of 20, 52, and 85 percent are shown in plate 1 (there were no deep penetrations made in test series 1 and 2, plate 1a); plate 2 contains similar data for tests in mortar sand at relative densities of 34, 55, and 92 percent. In general, the goal of producing test sections that did not vary in density with depth was achieved. The corresponding cone penetration tests indicated a tendency for the rate of increase in penetration resistance with depth to begin decreasing at depths greater than 10 to 15 cone diameters (23 to 34 cm), particularly in the loose and medium-dense sections. Vesić[12,13] published similar findings.

34. Also important is the fact that gravimetric density measurements made at the surface of each of several layers during construction agreed with nuclear density measurements made at corresponding locations after construction (see plate 1). This means that the construction operations on layers above a particular layer did not cause any appreciable increase in

density of those lower layers. Thus, gravimetric density measurements made during construction appear adequate for describing the density-depth profile for test sections as deep as those used in this program.

Examination of Pressure-Sinkage Relations

35. Pressure-sinkage data were obtained for plates alone or plates surmounted by smooth- and rough-walled cylinders in the two sands, each prepared to three relative densities. However, not all of the footings were used in each test series (see tabulation in paragraph 17). The data from tests conducted with plates in Yuma sand at the three levels of density are the most complete, and the shapes of the penetration resistance curves (plate 3) are similar to those obtained from tests with both types of cylindrical footings. The most complete set of data for the mortar sand was obtained from tests with the smooth-walled cylinders. Curves representing these data are shown in plate 4. At the lowest densities, the pressure-sinkage curves for a variety of footing diameters tend to coincide. As density increases, the curves first begin to separate and finally, at the highest densities, cross. That the relations changed with density illustrates the necessity for considering a wide range of densities or relative densities in any evaluation of bearing capacity equations based on dimensional analysis or theory. For example, the adequacy of a dimensionless relation is not really assessed when the effort is limited to tests at a low density, but the ability to achieve a collapse of pressure-sinkage curves, such as those representing the densest mortar and Yuma sand, is a true test of the adequacy of the dimensionless equations involved (see paragraphs 39-50).

Effects of Footing Configuration

Plates versus cylinders

36. Because of the difference in boundary conditions, a difference in the shape of the penetration resistance (pressure on the base) curves for plates and cylinders (smooth or rough sidewalls) was anticipated. However, there are no basic differences in the shape of the curves, as can be

seen from the representative curves in plate 5, although the pressures on the bases of the cylinders tend to be slightly larger. These data represent penetration tests in sand at both high and low relative densities.

Smooth-walled versus
rough-walled cylinders

37. When tests with smooth-walled and rough-walled cylinders were compared, the following questions were raised:

- a. Are there changes in the pressures on the bases?
- b. Are there changes in the vertical sidewall friction per unit area?

Results from tests with two sizes of smooth-walled and rough-walled cylinders in sands of different consistencies are compared in plate 6. For z/d values in excess of approximately 0.5, the pressure on the base P is somewhat greater for the rough-walled cylinders in most comparative penetrations. Rough cylinders produce higher vertical pressures around the plate and, thereby, increase the resistance or bearing capacity. However, the data do not reveal any consistent variations that might be related to a specific behavioral characteristic of the soil.

38. A comparison of the relations of sidewall friction per unit area P_s versus penetration parameter z/d obtained from the same group of tests shown in plate 6 is presented in plate 7. P_s is slightly larger for the rough-walled cylinders, but there is no systematic variation in P_s with density or friction angle in either sand. P_s is highest for the densest material in each case, but the tests at the lowest densities indicated higher sidewall friction per unit area than did the tests at the intermediate densities in seven of the eight cases illustrated. This information definitely indicates that no simple equation can be established to relate P_s to a specific soil property, such as friction angle, void ratio, consistency, or relative density.

Evaluation of Dimensionless Forms

Pressure parameter
versus penetration parameter

39. Individual data curves. The first step in evaluating equation 7,

$P/\gamma d = f(z/d, \phi)$, was to establish the relation between $P/\gamma d$ (the pressure parameter) and z/d (the penetration parameter). To do this, the data from tests in Yuma and mortar sands with circular plates and smooth- and rough-walled cylinders were plotted by using these two parameters as shown in plates 8-13. These data represent relative densities of 20, 52, and 85 percent in Yuma sand and 34, 55, and 92 percent in mortar sand. The plate data collapse about as well as the cylinder data; the degree of collapse for plates and cylinders is somewhat better at the lower densities. There is some tendency, however, for data from plates and cylinders 10 cm in diameter and smaller to separate from the rest of the data. This separation possibly may be attributed to the interlocking of sand grains, which makes the soil behave as though it had a small amount of cohesion. Triaxial tests on both sands have indicated cohesive strength up to 6.895 kN/m^2. Considering the general bearing capacity relation (equation 2), it can be concluded that this would tend to cause a separation, because the portion of the penetration resistance attributable to the apparent cohesive strength of the soil increases as the footing diameter decreases. Vesić[12,13] has indicated that the mode of failure in cohesionless material changes from punching, to local, to general shear, and is related to relative density and the magnitude of the penetration parameter. This difference in failure mode, if it occurs, would tend to cause the data from the tests with small footings to separate from the main group.

40. The data led to the conclusion that pressure-sinkage relations for large footings in sand can be predicted from model tests with a fair degree of accuracy if the linear scale is not greater than 5 to 1. Thus, model footings should be as large as practical to enhance accuracy. At least some of the laboratory experiments that have been conducted to evaluate and/or generate bearing capacity relations or theories have been based, at least in part, on tests with small model footings. Extension of these data to considerably larger footings may have been responsible for the lack of agreement between bearing capacity theory and laboratory test results.

41. Summary curves. The similarity in the data obtained for the three types of footings having been illustrated, summary curves representing the average results from the tests conducted with only the smooth-walled

cylinders in Yuma and mortar sands are shown in plate 14. A unique relation is shown for each test series (constant relative density), and the magnitude of $P/\gamma d$ at any value of z/d increases in both sands as the relative density increases. The conclusion at this point is that an additional parameter, such as friction angle, must be considered in the analysis, or that some indicator of soil property that reflects the combined effect of density and friction angle should be considered. This is in agreement with the functional relation in equation 7.

Variations in pressure-sinkage relations with friction angle

42. A unique relation of the form $P/\gamma d = f(z/d)$ was shown to exist for a given density or friction angle for each sand. The next step was to construct cross plots to relate the friction angle to the pressure parameter $P/\gamma d$ at several values of the penetration parameter z/d. These plots indicated that the relation of the friction angle to the pressure parameter can be described by the following equation:

$$P/\gamma d = a \tan \phi^{7}$$

or

$$a = P/\gamma d \tan \phi^{-7} \qquad (8)$$

where a is a constant of proportionality. This led to the conclusion that for each constant value of the penetration parameters, there is a corresponding value of the term $P/\gamma d \tan \phi^{-7}$. This information for both sands is plotted in plate 15. The values of density, relative density, and triaxial friction angle of the two sands are as follows:

Yuma Sand			Mortar Sand		
Density γ kN/m^3	Relative Density D_r, %	Triaxial Friction Angle ϕ deg	Density γ kN/m^3	Relative Density D_r, %	Triaxial Friction Angle ϕ deg
14.14	20	35	14.72	34	30
14.93	52	36.5	15.05	55	31
15.87	85	40	16.40	92	36

43. While the data for a given type of sand collapse readily in

plate 15, the data for the two sands differ widely. In reexamining the plots for Yuma and mortar sands that are at comparable relative densities in plate 14 (the actual densities are very nearly equal in this case), the penetration parameters at given values of the pressure parameters can be seen to agree within a few percentage points. Thus, the fact that the curves for the two sands are separated when a friction angle term is added indicates that the friction angle may be in error for one of these sands. Other available information on the two sands indicates that the friction angle may be low for the mortar sand (see paragraphs 44-48). A comparison of these data with theoretical calculations (see paragraphs 51-53) corroborates the assumption that the effect of friction angle on the mortar sand is larger than implied by conventional triaxial compression tests. Other tests reported by WES[14] indicate that the triaxial tests give an unreasonably low friction angle for the mortar sand (termed Reid-Bedford in reference 14).

44. Some existing literature suggests that volume changes and associated friction angle changes during the penetration test might contribute to the problem. Other literature suggests that an inaccuracy in the triaxial test as a means of measuring friction angle should be considered. Broms[15] indicated that a shell effect of small triaxial specimens produced an effective reduction in the minor principal stress σ_3 , i.e. σ_3 was less than the confining pressure in the triaxial chamber; therefore, the computed friction angle, when based on the confining pressure, is too small.* He indicated further that the measured friction angle from standard triaxial tests may be as much as 4 deg too small for very dense sand, and that for loose sand the standard measurement may be adequate.**

45. Cornforth[16] has pointed out that while the peak friction angle based on the maximum shear stresses for plane strain and dense sand in

---

* "A difference in the friction angle, ϕ , of 3-4 deg is sufficient to explain the difference observed by a number of investigators for dense sand between extension and compression tests and between the calculated and measured bearing capacity of model footings."

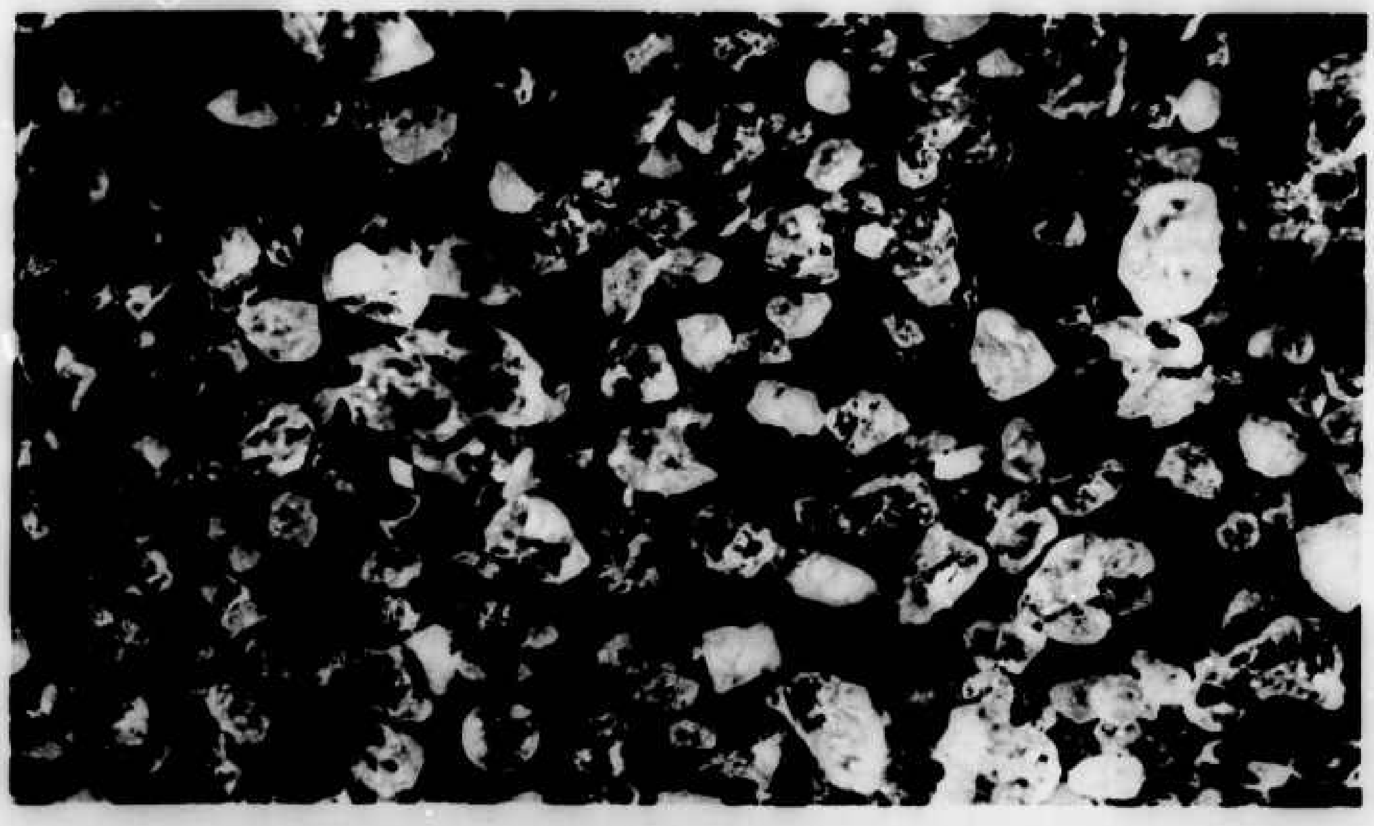
** "Experiments by Brinch Hansen (1961) and Tcheng (1957) have indicated that the bearing capacity of model footings placed on dense sand may exceed considerably that predicted by existing bearing capacity theories if the shear-strength parameters determined from standard triaxial compression tests are used in the analysis of the test data. However, close agreement was found for footings located on medium to loose sand."

general is 10 percent higher than the corresponding triaxial test friction angles, the friction angles from the plane strain generally match the triaxial values quite well when the ultimate shear stress values are used. This finding agrees generally with the limited data available on Yuma sand, but not with those available for mortar sand.

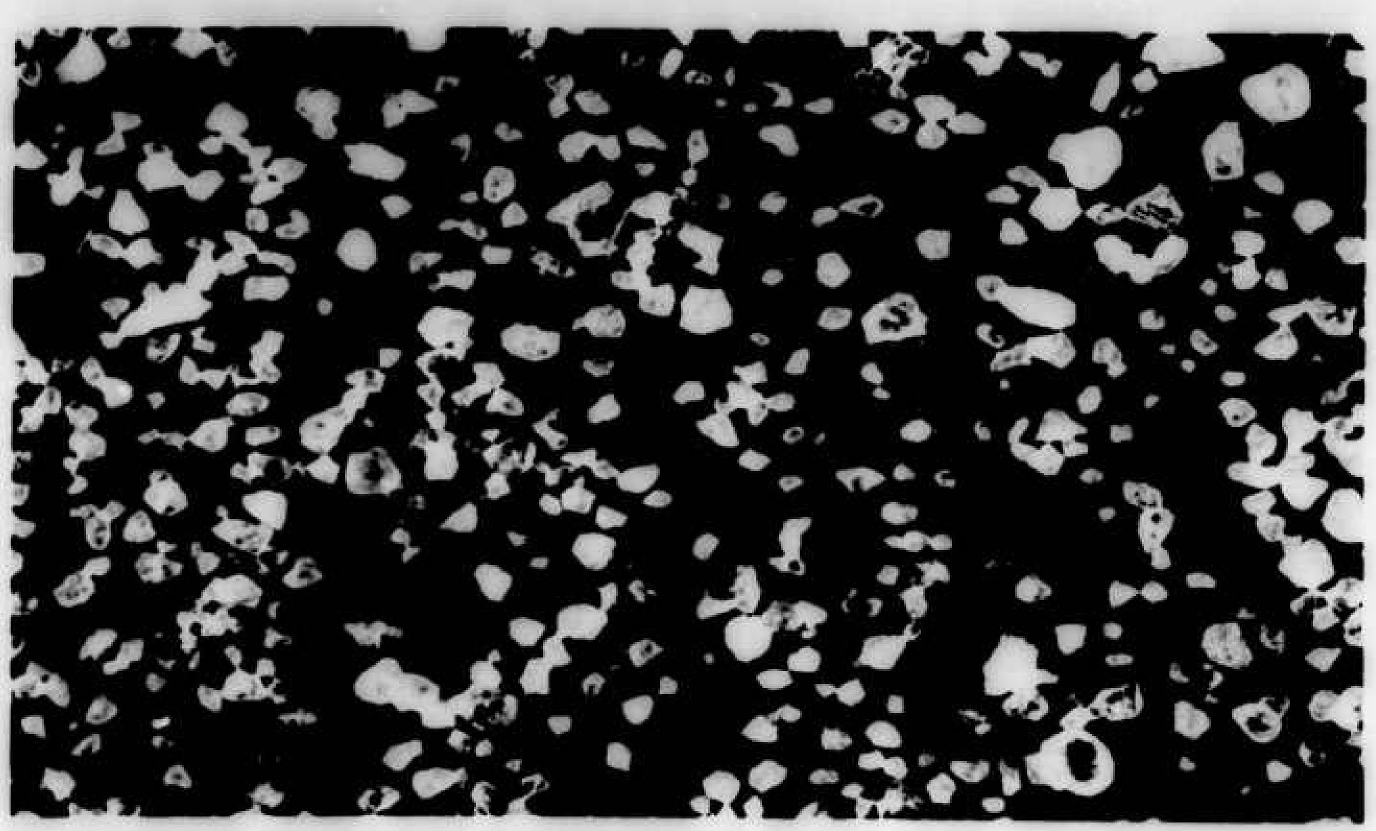
46. Plane strain tests were recently conducted on both sands by personnel at the Massachusetts Institute of Technology. Results of these tests are compared with triaxial and direct shear data in plate 16. The plane strain data indicate that the peak friction angle (based on the maximum shear stress) for one sand may be approximately equal to that of the other sand at a given density. The data definitely indicate that friction angles from plane strain tests are higher than those obtained from triaxial tests at the high dry densities, and may be higher in the entire density range. The triaxial test indicates a difference of 5 deg or more in the friction angle of the two sands at a given density. The ultimate values of the friction angles from the plane strain test in Yuma sand indicated friction angles approximately equal to triaxial test results. On the other hand, plane strain ultimate friction angles for the mortar sand were noticeably higher than those taken from triaxial tests in the same material. In the photograph of both sands (fig. 12), mortar sand is seen to be coarser and more angular, and the surfaces of the individual grains are not as well polished as those of the Yuma sand, and thus the degree of interlocking may be greater. On the basis of the foregoing observations and an examination of the enlarged photographs of the sand grains, it seems reasonable to assume that the shell effect in triaxial specimens is greater for the mortar sand than for the Yuma sand. The data from triaxial and plane strain tests seem to corroborate this assumption.

47. The following friction angles for the mortar sand were estimated, based on the ultimate values from the plane strain tests, which were assumed to correspond to triaxial test data corrected for shell effect:

Density γ kN/m^3	Relative Density D_r, %	Friction Angle ϕ, deg
14.72	34	33
15.05	55	35
16.40	92	40



a. Mortar sand



b. Yuma sand

Fig. 12. Sand grains magnified 25 times

Estimating these friction angles was justified by the correspondence of the triaxial friction angle data for the Yuma sand to the ultimate values from the plane strain tests, the hypothesized triaxial shell effects in mortar sand, and the high bearing capacity of the mortar sand (compared to computed values based on Brinch Hansen's equation and triaxial friction angles).

48. When these friction angles are substituted for the original triaxial values in the relation $P/\gamma d = f(z/d \cdot \tan \phi^{7})$, then a single curve can be developed to delineate the relation for both sands (see plate 17).

Other dimensionless forms

49. Penetration resistance gradient. The functional equation $P/\gamma d = f(z/d, \phi)$ (equation 7) states that the pressure-sinkage relation for a cohesionless soil is a function not only of the soil's unit weight, but also of the angle of internal friction. At this point, some reconsideration is appropriate; perhaps a term that reflects changes in γ and ϕ can be substituted for γ and/or ϕ . The experiences in dimensional scaling of tire performance data[17] and those derived from dynamic loading of model footings[14] suggest that the penetration resistance gradient G (rate of increase in strength with depth computed from cone penetration tests) is sensitive to changes in both γ and ϕ . If this is a valid statement, a new functional relation can be written as follows:

$$P/Gd = f(z/d) \tag{9}$$

(A similar form was used in the references cited above.) One problem in using the parameter G is that a decision must be made as to what total depth should be considered in computing the appropriate value, i.e. to what depth and degree is the material beneath the plate being stressed, and what is the anticipated depth of penetration. This means computing G for each size of footing. Obviously, some simplification is desirable so that a single value of G can be obtained for a homogeneous sand layer. Since no pronounced layers were noticeable from the cone penetration tests, and the cone penetration resistance was not linear over depths much greater than 15 cm, even in the uniform densities represented in the test sections, the value of G was based on the strength of the 0- to 15-cm layer. When the data from plate 14 ($P/\gamma d$ versus z/d for each of the six test series with smooth-walled cylinders) are converted to the form P/Gd versus z/d , the relation shown in plate 18 is obtained. In general, the data appear to collapse. That the parameter G tends to collapse the data for both sands into a single curve corroborates the statement that the friction angles used for the mortar sand in the development of plate 15 were too low, i.e. the plot indicates that the friction angles are comparable for the two sands. Results from one test series (No. 7) do not match those of the other five series, probably because the sand for series 7 was prepared by a method different from that used for the other five (see paragraph 9).* Only when the values of G , γ , and ϕ were related did the results from series 7 vary from those of the other series.

50. Relative density. Relative density is a soil property that is related to friction angle. Since it, too, is dimensionless, examination of the following relation seemed reasonable:

$$P/\gamma d = f\left(\frac{z}{d} , D_r\right) \tag{10}$$

A satisfactory collapse of the test data was not achieved. The difficulty in determining relative density (various methods exist) and the sensitivity of the form of the mathematical relation finally used, i.e.

$$P/\gamma d \cdot 1/D_r = f\left(\frac{z}{d}\right)$$

to small changes in relative density are ascribed as the reasons for the failure of the data to collapse.

Comparison of Measured and Computed Relations

51. Following the development of the dimensionless equations,

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* The WES has experimented with methods of preparing dry sand sections at various densities, including sprinkling, rolling with pneumatic tires, vibrating of layers, vibrating of entire specimens, and others. The relations among G , γ , and ϕ are not unique, but vary with the method of preparation. A satisfactory explanation of this phenomenon has not been found.

comparison of the data obtained with results computed by bearing capacity equations developed by others, specifically those of Meyerhof and Brinch Hansen, seemed appropriate. Since the equations of these two researchers have already been compared (paragraphs 18-25), the results obtained from the dimensionless equations herein will be compared with results obtained only by Brinch Hansen's equation.

52. Average curves for each series representing tests in Yuma and mortar sands are compared in plates 19a and 19b, respectively, with curves based on the Brinch Hansen equation (equation 4). For the Yuma sand, friction angles of 40, 36.5, and 35 deg, corresponding to results of the triaxial tests and densities shown in plate 1, were used. The Yuma sand data agree quite well with the computed results.

53. The curves representing computed values for mortar sand tests are based on equation 4 and on friction angles computed from the ultimate shear stresses measured during the plane strain tests. When these values are used, the mortar sand data agree reasonably well with theory. On the other hand, when triaxial test friction angles are used, the footing pressures computed by equation 4 are approximately one-half those measured during the mortar sand test series. For example, at a z/d value of 2.6, taken from the curve representing the densest material, the measured value of $P/\gamma d$ is approximately 486. The computed value of $P/\gamma d$, using equation 4 and the corresponding triaxial friction angle of 36.3 deg, is approximately 230.

54. A change in friction angle of 3 to 4 deg can cause a change in the computed bearing capacity by a factor of approximately 2 when the friction angle is generally within the 30- to 40-deg range. In light of this fact and the problem of obtaining a reliable friction angle measurement, results of model-footing tests to predict bearing capacity of cohesionless soils may be preferred to a theory-based prediction that requires an accurate friction angle measurement.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

55. Based on the interpretation of the data herein, the conclusions are:

a. Controlled sprinkling of sand can be used to produce a uniform sand density (paragraphs 33-34).

b. The penetration resistance versus depth data, expressed by the dimensionless parameters $P/\gamma d$ and z/d, form a single curve for a given sand. This is in conformity with the bearing capacity theories (paragraphs 39-41).

c. There are no basic differences in the shape of penetration resistance curves for plates and cylinders. The pressures on the bases of the cylinders are slightly larger, however. The function of the cylinders is primarily to prevent collapse of sand walls above the plate. Tests confirm theoretical considerations (paragraph 36).

d. Consistent penetration data for plates and cylinders were obtained because of the uniformity of the soil and small influence of sidewall friction. The data should be very valuable in future investigations of basic bearing capacity factors (depth factors).

e. The conclusions above indicate that the bearing capacity of a given plate may be estimated either by model tests or by the bearing capacity theories, but the latter also require accurate determination of the angle of internal friction ϕ, which may be difficult (paragraphs 44-48).

f. Standard cone penetration tests, performed to verify the uniformity of the sand density, furnished curves that are nearly straight for the upper 10 to 15 cm. Introducing this slope as an additional variable permitted the dimensionless relations for two different sands to be represented by a single curve (paragraph 49).

g. Pressures on the bases P and cylinder sidewall friction per unit area P_s are greater for rough-walled cylinders than for smooth-walled ones. There appears to be no relation between the magnitude of P_s and any specific soil property (paragraphs 37 and 38).

Recommendations

56. With respect to experience gained from penetration tests in sand, it is recommended that:

a. Triaxial and plane strain tests be conducted on sands with various grain sizes, shapes, and surface roughnesses to seek a more reliable method of determining friction angles of cohesionless soils.

b. Penetration tests be conducted in sand to study shape effects (i.e. squares, circles, and rectangles of various aspect ratios).

c. Penetration tests be conducted in layered frictional soils.

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Table 1

Test Data

Depth of Penetration cm	Point Force, N Plates, cm Diam 2.54	5.08	10.16	20.32	30.48	40.64	60.96	Smooth-Walled Cylinders, cm Diam 5.08	10.16	20.32	30.48	40.64	60.96	Rough-Walled Cylinders, cm Diam 5.08	10.16	20.32	30.48	40.64
Test Series 1, Yuma Sand																		
1	7	37	183	726	1,346	2,534	--	--	204	823	1,492	2,682	--	--	132	--	1,619	--
2	13	55	266	1,155	2,220	3,973	--	--	289	1,317	2,530	3,943	--	--	268	--	2,772	--
3	18	75	348	1,575	3,214	5,680	--	--	378	1,819	3,744	5,891	--	--	392	--	4,184	--
4	24	97	436	2,044	4,173	7,491	--	--	469	2,209	4,972	7,670	--	--	508	--	5,434	--
5	29	119	519	2,400	5,080	9,123	--	--	563	2,541	6,006	9,409	--	--	634	--	6,719	--
6	31	139	603	2,783	5,894	10,679	--	--	641	2,833	6,921	10,851	--	--	746	--	7,938	--
7	40	161	695	3,113	6,811	12,342	--	--	701	3,123	7,612	12,454	--	--	832	--	9,016	--
8	44	185	781	3,381	7,533	13,827	--	--	768	3,439	8,417	13,912	--	--	926	--	10,023	--
9	46	207	867	3,700	8,369	15,222	--	--	840	3,770	9,024	15,338	--	--	1,010	--	10,806	--
10	53	229	942	3,993	8,947	16,515	--	--	896	4,104	9,812	16,580	--	--	1,091	--	11,277	--
11	55	246	1,023	4,233	9,722	17,655	--	--	941	4,351	10,542	17,723	--	--	1,166	--	11,867	--
12	59	271	1,129	4,512	10,501	18,938	--	--	1,016	4,641	11,260	18,901	--	--	1,265	--	12,729	--
13	62	288	1,221	4,860	11,169	20,143	--	--	1,103	4,955	11,906	20,057	--	--	1,349	--	13,490	--
14	66	308	1,313	5,139	11,772	21,716	--	--	1,188	5,283	12,536	21,401	--	--	1,417	--	14,252	--
15	66	326	1,404	5,416	12,564	22,785	--	--	1,285	5,616	13,156	22,590	--	--	1,505	--	15,145	--
16	73	343	1,492	5,683	13,101	24,074	--	--	1,355	5,978	13,741	23,692	--	--	1,584	--	15,827	--
17	73	359	1,573	5,977	13,831	25,313	--	--	1,454	6,306	14,480	24,937	--	--	1,650	--	16,614	--
18	77	376	1,668	6,327	14,553	26,477	--	--	1,538	6,612	15,136	26,284	--	--	1,736	--	17,371	--
19	81	392	1,753	6,626	15,250	27,694	--	--	1,602	6,856	15,752	27,408	--	--	1,804	--	18,093	--
20	84	403	1,833	6,838	16,014	28,965	--	--	1,701	7,149	16,487	28,684	--	--	1,896	--	18,691	--
21	86	411	1,912	7,165	16,623	29,982	--	--	1,767	7,444	17,204	29,688	--	--	1,969	--	19,536	--
22	86	425	1,991	7,495	17,340	31,178	--	--	1,847	7,701	17,798	30,867	--	--	2,042	--	20,178	--
23	88	433	2,070	7,757	17,983	32,558	--	--	1,931	7,986	18,515	32,142	--	--	2,116	--	21,067	--
24	90	449	2,141	8,076	18,682	33,715	--	--	1,977	8,229	19,140	33,400	--	--	2,180	--	21,916	--
25	92	455	2,213	8,395	19,461	35,123	--	--	2,046	8,533	19,840	34,759	--	--	2,257	--	22,726	--
26	95	464	2,288	8,708	20,075	36,179	--	--	2,124	8,761	20,478	35,805	--	--	2,321	--	23,509	--
27	--	477	2,350	8,961	20,792	37,572	--	--	2,193	9,044	21,177	37,111	--	--	2,389	--	24,350	--
28	--	486	2,405	9,304	21,358	38,779	--	--	2,251	9,362	21,815	38,290	--	--	2,462	--	25,234	--
29	--	--	2,468	9,658	22,103	40,075	--	--	2,341	9,591	22,449	39,544	--	--	2,534	--	26,026	--
30	--	--	--	10,006	22,823	41,351	--	--	2,402	9,887	23,219	40,870	--	--	2,611	--	26,849	--
31	--	--	--	10,265	23,456	42,565	--	--	2,467	10,188	23,804	42,012	--	--	2,693	--	27,632	--
32	--	--	--	10,580	24,101	43,932	--	--	2,546	10,535	24,763	43,309	--	--	2,765	--	28,662	--
33	--	--	--	10,890	24,864	45,126	--	--	2,614	10,860	25,542	44,629	--	--	2,829	--	29,511	--
34	--	--	--	11,189	25,722	46,490	--	--	2,682	11,120	26,404	46,105	--	--	2,895	--	30,307	--
35	--	--	--	11,557	26,497	47,839	--	--	2,759	11,430	27,113	47,431	--	--	2,963	--	31,271	--
36	--	--	--	11,977	27,192	49,172	--	--	2,830	11,766	27,922	48,652	--	--	3,027	--	31,693	--
37	--	--	--	12,272	27,936	50,655	--	--	2,892	12,087	28,609	49,908	--	--	3,093	--	33,070	--
38	--	--	--	12,613	28,708	51,992	--	--	2,974	12,351	29,454	51,416	--	--	3,155	--	33,933	--
39	--	--	--	12,945	29,526	53,563	--	--	3,035	12,653	30,215	52,910	--	--	3,223	--	34,729	--
40	--	--	--	13,284	30,169	54,978	--	--	3,104	12,929	31,011	54,035	--	--	3,280	--	35,627	--
41	--	--	--	13,570	30,837	56,128	--	--	3,162	13,244	31,698	55,379	--	--	--	--	36,542	--
42	--	--	--	13,851	31,680	57,442	--	--	--	[illegible]	32,353	56,756	--	--	--	--	37,497	--
43	--	--	--	--	32,410	58,815	--	--	--	13,965	33,194	58,247	--	--	--	--	38,627	--
44	--	--	--	--	33,277	[illegible]	--	--	--	14,230	34,065	59,805	--	--	--	--	39,653	--
45	--	--	--	--	34,058	61,793	--	--	--	14,560	34,901	61,177	--	--	--	--	40,673	--
46	--	--	--	--	34,888	63,395	--	--	--	14,824	35,719	62,573	--	--	--	--	41,611	--
47	--	--	--	--	35,803	64,900	--	--	--	15,087	36,621	64,117	--	--	--	--	42,632	--
48	--	--	--	--	36,670	66,383	--	--	--	15,414	37,426	65,558	--	--	--	--	43,762	--
49	--	--	--	--	37,455	67,383	--	--	--	15,731	38,284	67,036	--	--	--	--	44,669	--
50	--	--	--	--	38,383	69,416	--	--	--	16,101	39,081	68,577	--	--	--	--	45,910	--
51	--	--	--	--	39,118	70,983	--	--	--	16,356	39,877	70,017	--	--	--	--	46,855	--

(Continued)

(1 of 8 sheets)

Table 1 (Continued)

Depth of Penetration cm	Point Force, N																	
	Plates, cm Diam							Smooth-Walled Cylinders, cm Diam						Rough-Walled Cylinders, cm Diam				
	2.54	5.08	10.16	20.32	30.48	40.64	60.96	5.08	10.16	20.32	30.48	40.64	60.96	5.08	10.16	20.32	30.48	40.64
								Test Series 1, Yuma Sand (Continued)										
52	--	--	--	--	40,049	72,888	--	--	--	16,681	40,911	71,684	--	--	--	--	48,083	--
53	--	--	--	--	40,955	74,699	--	--	--	17,024	41,910	73,126	--	--	--	--	48,937	--
54	--	--	--	--	41,884	76,401	--	--	--	17,358	42,900	74,722	--	--	--	--	50,024	--
55	--	--	--	--	42,832	78,036	--	--	--	--	43,342	76,397	--	--	--	--	51,101	--
56	--	--	--	--	43,795	79,952	--	--	--	--	44,801	78,193	--	--	--	--	52,545	--
57	--	--	--	--	44,642	81,842	--	--	--	--	45,769	79,979	--	--	--	--	53,451	--
58	--	--	--	--	45,606	83,912	--	--	--	--	46,772	82,118	--	--	--	--	54,727	--
59	--	--	--	--	46,453	85,822	--	--	--	--	47,793	84,081	--	--	--	--	56,183	--
60	--	--	--	--	47,489	87,910	--	--	--	--	48,805	86,082	--	--	--	--	57,011	--
61	--	--	--	--	48,442	89,659	--	--	--	--	49,658	--	--	--	--	--	58,133	--
62	--	--	--	--	49,460	91,896	--	--	--	--	50,648	--	--	--	--	--	59,659	--
63	--	--	--	--	--	94,175	--	--	--	--	51,687	--	--	--	--	--	61,059	--
64	--	--	--	--	--	96,221	--	--	--	--	52,690	--	--	--	--	--	--	--
								Test Series 2, Yuma Sand										
1	13	77	376	1,428	1,982	9,728	9,262	--	310	1,195	3,876	--	--	--	361	--	3,329	--
2	20	92	506	2,278	4,031	16,865	18,062	--	497	1,843	5,566	--	--	--	444	--	4,704	--
3	26	121	594	3,039	6,444	21,908	27,843	--	625	2,575	7,590	--	--	--	548	--	6,602	--
4	37	147	686	3,431	8,204	26,004	38,033	--	735	3,228	8,994	--	--	--	662	--	8,301	--
5	44	174	770	3,894	9,479	29,757	47,053	--	854	3,760	9,953	--	--	--	774	--	9,656	--
6	55	200	871	4,276	10,790	34,197	54,956	--	966	4,199	10,886	--	--	--	889	--	10,659	--
7	59	231	970	4,819	11,959	37,862	61,534	--	1,082	4,571	11,651	--	--	--	1,012	--	11,491	--
8	68	257	1,063	5,331	13,003	41,659	67,078	--	1,192	5,046	12,126	--	--	--	1,129	--	12,305	--
9	79	286	1,157	5,687	13,950	44,990	72,767	--	1,309	5,425	12,769	--	--	--	1,250	--	13,039	--
10	84	319	1,269	6,030	15,074	48,369	77,827	--	1,415	5,874	13,213	--	--	--	1,368	--	13,704	--
11	92	343	1,355	6,564	16,016	52,078	81,901	--	1,551	6,190	13,644	--	--	--	1,472	--	14,436	--
12	97	374	1,467	6,884	17,163	55,361	85,228	--	1,674	6,606	14,885	--	--	--	1,597	--	15,193	--
13	101	398	1,577	7,351	18,007	59,171	88,220	--	1,795	7,172	15,453	--	--	--	1,716	--	16,117	--
14	110	427	1,687	7,819	18,945	63,338	92,981	--	1,910	7,626	16,535	--	--	--	1,828	--	16,933	--
15	114	458	1,791	8,473	19,940	66,757	96,017	--	2,031	8,036	17,028	--	--	--	1,954	--	17,838	--
16	117	482	1,901	8,838	20,722	71,280	99,545	--	2,154	8,495	17,860	--	--	--	2,083	--	18,652	--
17	125	510	2,011	9,256	21,633	74,835	103,448	--	2,279	8,912	18,581	--	--	--	2,211	--	19,455	--
18	128	532	2,105	9,870	22,416	78,650	105,556	--	2,391	9,379	19,650	--	--	--	2,332	--	20,297	--
19	132	557	2,204	10,369	23,393	82,544	107,782	--	2,517	9,848	20,324	--	--	--	2,462	--	21,283	--
20	136	579	2,308	10,822	24,464	86,803	111,276	--	2,636	10,328	21,287	--	--	--	2,592	--	22,176	--
21	141	598	2,398	11.312	25,357	89,835	114,593	--	2,746	10,709	22,088	--	--	--	2,713	--	23,054	--
22	143	623	2,512	12,068	26,460	94,463	118,518	--	2,869	11,237	22,905	--	--	--	2,836	--	24,006	--
23	150	645	2,614	12,497	27,659	97,447	122,575	--	2,995	11,746	23,764	--	--	--	2,968	--	24,999	--
24	152	667	2,724	12,972	28,619	102,115	126,165	--	3,115	12,263	24,587	--	--	--	3.091	--	26,004	--
25	156	684	2,823	13,555	29,326	106,576	129,769	--	3,238	12,780	25,489	--	--	--	3,234	--	26,809	--
26	156	706	2,935	14,107	30,157	110,857	133,240	--	3,351	13,305	26,242	--	--	--	3,377	--	27,707	--
27	163	730	3,040	14,574	31,179	115,579	138,287	--	3,467	13,792	27,073	--	--	--	3,531	--	28,596	--
28	165	755	3.146	15,210	32,357	120,216	142,049	--	3,593	14,245	27,746	--	--	--	3,681	--	29,405	--
29	169	774	3,249	15.722	33,526	124,735	145,266	--	3,707	14,776	28,653	--	--	--	3,821	--	30,272	--
30	176	794	3,346	16,211	34,508	128,985	149,221	--	3,826	15,229	29,432	--	--	--	3,967	--	31,295	--
31	178	816	3,450	16,772	35,516	133,421	153,454	--	3,949	15,729	30,215	--	--	--	4,090	--	31,266	--
32	187	843	3,557	17,422	36,490	138,085	157,629	--	4,094	16,261	30,994	--	--	--	4,242	--	33,042	--
33	194	865	3,661	17,849	37,472	143,132	162,043	--	4,220	16,729	31,997	--	--	--	4,398	--	34,030	--
34	198	891	3,769	18,534	38,534	149,234	165,536	--	4,367	17,244	32,758	--	--	--	4,552	--	34,947	--
35	205	913	3,868	18,815	39,329	154,576	168,889	--	4,490	17,724	33,757	--	--	--	4,708	--	35,928	--
36	211	935	3,964	19.438	40,200	160,067	173,580	--	4,629	18,217	34,470	--	--	--	4,860	--	36,881	--

(Continued)

Table 1 (Continued)

Depth of Penetration cm	Point Force, N Plates, cm Diam 2.54	5.08	10.16	20.32	30.48	40.64	60.96	Smooth-Walled Cylinders, cm Diam 5.08	10.16	20.32	30.48	40.64	60.96	Rough-Walled Cylinders, cm Diam 5.08	10.16	20.32	30.48	40.64
								Test Series 2, Yuma Sand (Continued)										
37	216	955	4,068	19,963	41,076	--	178,345	--	4,750	18,754	35,240	--	--	--	5,005	--	37,844	--
38	222	977	4,167	20,390	42,280	--	182,542	--	4,882	19,179	36,133	--	--	--	5,166	--	38,801	--
39	227	999	4,259	20,973	43,071	--	186,819	--	5,012	19,652	36,832	--	--	--	5,313	--	39,697	--
40	233	1019	4,354	21,382	44,267	--	190,854	--	5,144	20,082	37,752	--	--	--	5,460	--	40,700	--
41	235	1043	4,442	22,054	45,053	--	194,655	--	5,265	20,509	38,623	--	--	--	5,599	--	41,602	--
42	240	1071	4,545	22,575	46,195	--	199,328	--	5,408	20,973	39,468	--	--	--	5,826	--	42,511	--
43	242	1093	--	23,091	47,293	--	203,539	--	5,542	21,475	40,273	--	--	--	--	--	43,353	--
44	246	1109	--	23,389	48,102	--	207,618	--	5,678	21,934	41,303	--	--	--	--	--	44,266	--
45	--	1135	--	23,994	49,222	--	211,780	--	--	22,348	42,134	--	--	--	--	--	45,245	--
46	--	1155	--	24,479	50,248	--	216,801	--	--	22,850	43,072	--	--	--	--	--	46,264	--
47	--	--	--	24,764	51,026	--	220,417	--	--	23,307	43,776	--	--	--	--	--	47,214	--
48	--	--	--	25,076	51,835	--	225,015	--	--	23,709	44,581	--	--	--	--	--	48,1[illegible]	--
49	--	--	--	25,628	52,804	--	229,543	--	--	24,203	45,426	--	--	--	--	--	48,972	--
50	--	--	--	26,179	54,035	--	233,762	--	--	24,594	46,389	--	--	--	--	--	49,911	--
51	--	--	--	--	54,790	--	238,022	--	--	24,931	47,018	--	--	--	--	--	50,778	--
52	--	--	--	--	56,021	--	242,888	--	--	25,289	47,766	--	--	--	--	--	51,904	--
53	--	--	--	--	56,999	--	248,309	--	--	25,771	48,637	--	--	--	--	--	52,897	--
54	--	--	--	--	58,234	--	252,982	--	--	26,198	49,535	--	--	--	--	--	54,074	--
55	--	--	--	--	59,212	--	--	--	--	26,668	50,468	--	--	--	--	--	55,046	--
56	--	--	--	--	60,372	--	--	--	--	27,133	51,251	--	--	--	--	--	55,875	--
57	--	--	--	--	61,145	--	--	--	--	27,591	52,250	--	--	--	--	--	56,857	--
58	--	--	--	--	62,274	--	--	--	--	27,993	52,963	--	--	--	--	--	57,741	--
59	--	--	--	--	63,345	--	--	--	--	28,500	53,768	--	--	--	--	--	58,617	--
60	--	--	--	--	64,131	--	--	--	--	29,442	54,375	--	--	--	--	--	59,670	--
61	--	--	--	--	65,189	--	--	--	--	--	55,449	--	--	--	--	--	60,559	--
62	--	--	--	--	66,509	--	--	--	--	--	56,588	--	--	--	--	--	61,455	--
63	--	--	--	--	67,589	--	--	--	--	--	57,662	--	--	--	--	--	62,643	--
64	--	--	--	--	68,535	--	--	--	--	--	59,101	--	--	--	--	--	63,850	--
65	--	--	--	--	69,935	--	--	--	--	--	60,130	--	--	--	--	--	--	--
66	--	--	--	--	71,060	--	--	--	--	--	--	--	--	--	--	--	--	--
								Test Series 7, Yuma Sand										
1	--	86	799	4,589	9,030	--	--	105	684	4,583	12,940	25,309	45,232	145	807	4,107	13,490	19,382
2	--	120	1,124	8,118	17,455	--	--	129	1,159	7,850	21,905	43,456	86,037	172	1,089	6,182	21,960	37,937
3	--	186	1,201	9,306	27,548	--	--	174	1,258	8,901	29,249	56,148	121,374	223	1,228	7,007	29,225	53,170
4	--	238	1,362	9,108	31,962	--	--	236	1,399	9,110	31,792	65,443	147,413	273	1,353	7,394	32,362	64,057
5	--	289	1,527	9,249	32,094	--	--	294	1,591	8,752	31,739	69,949	166,812	346	1,558	7,773	32,173	69,575
6	--	360	1,718	9,398	31,513	--	--	361	1,773	8,928	31,273	71,792	182,912	422	1,729	8,131	31,825	71,911
7	--	422	1,923	9,865	31,759	--	--	430	1,958	9,907	31,825	71,210	195,359	481	1,969	8,540	31,962	72,791
8	--	484	2,125	10,300	32,824	--	--	497	2,191	10,758	32,591	70,200	203,029	561	2,213	8,967	32,956	72,719
9	--	551	2,343	10,881	33,383	--	--	565	2,427	11,284	33,770	70,176	206,496	629	2,446	9,508	34,052	71,412
10	--	627	2,567	11,722	34,720	--	--	632	2,662	11,928	34,747	71,001	210,412	721	2,713	10,168	35,147	72,221
11	--	693	2,772	12,456	35,794	--	--	706	2,886	12,558	35,926	72,340	213,857	797	2,974	10,910	36,115	73,572
12	--	780	3,038	13,244	37,334	--	--	797	3,122	13,312	37,186	73,852	214,860	881	3,190	11,836	37,334	75,110
13	--	867	3,276	13,895	39,169	--	--	885	3,370	14,161	38,599	75,770	215,265	982	3,447	12,848	39,068	76,848
14	--	942	3,487	14,538	40,427	--	--	973	3,667	15,094	39,875	78,280	216,924	1,070	3,731	13,682	40,431	78,705
15	--	1018	3,788	15,264	41,857	--	--	1,061	3,914	15,954	41,067	80,357	218,283	1,169	3,964	14,617	41,791	81,131
16	--	1096	4,077	16,126	43,529	--	--	--	4,244	16,905	42,484	83,004	220,633	--	4,250	15,429	43,129	84,172
17	--	1184	4,343	17,257	45,113	--	--	--	4,572	17,824	43,912	85,142	222,956	--	4,622	16,328	44,330	86,409
18	--	1282	4,666	18,062	46,609	--	--	--	4,902	18,665	45,443	87,300	227,087	--	5,018	17,266	46,051	88,325
19	--	1369	4,994	18,955	47,973	--	--	--	5,258	19,606	47,416	89,993	231,880	--	5,379	18,005	47,859	90,774
20	--	1460	5,302	19,769	49,724	--	--	1,542	5,634	20,506	48,974	92,791	236,367	1,718	5,735	18,869	49,513	92,917
21	--	1529	5,599	20,566	51,198	--	--	--	5,971	21,355	50,527	95,357	239,808	--	6,094	19,763	50,195	95,343

(Continued)

Table 1 (Continued)

Depth of Penetration cm	Point Force, N																	
	Plates, cm Diam							Smooth-Walled Cylinders, cm Diam						Rough-Walled Cylinders, cm Diam				
	2.54	5.08	10.16	20.32	30.48	40.64	60.96	5.08	10.16	20.32	30.48	40.64	60.96	5.08	10.16	20.32	30.48	40.64
								Test Series 7, Yuma Sand (Continued)										
22	--	1560	5,951	21,300	52,681	--	--	--	6,349	22,198	52,147	97,854	242,589	--	6,490	20,559	51,009	97,845
23	--	1738	6,279	22,180	54,278	--	--	--	6,723	23,175	53,445	100,315	247,750	--	6,838	21,417	51,735	100,064
24	--	1898	6,618	23,162	56,016	--	--	--	7,084	24,152	55,413	103,307	253,299	--	7,190	22,482	53,306	101,888
25	--	2020	6,930	24,121	57,534	--	--	2,044	7,427	25,227	56,903	106,061	257,826	2,431	7,553	23,404	54,776	103,677
26	--	2122	7,236	25,054	59,070	--	--	--	7,786	26,121	58,234	108,818	261,513	--	7,918	24,420	56,725	106,162
27	--	2258	7,506	25,978	60,374	--	--	--	8,140	27,031	59,512	112,006	266,397	--	8,254	25,436	58,498	108,858
28	--	2382	7,852	26,910	62,295	--	--	--	8,496	27,986	61,395	114,890	271,664	--	8,560	26,268	60,403	111,421
29	--	2524	8,173	28,195	64,526	--	--	--	8,840	28,904	63,241	116,962	275,479	--	8,985	27,245	62,770	114,694
30	--	2631	8,488	29,198	66,224	--	--	3,169	9,198	29,874	65,214	119,838	279,967	3,189	9,352	28,105	64,508	117,382
31	--	2751	8,813	30,127	67,751	--	--	--	9,550	30,826	67,014	122,474	284,966	--	9,715	28,882	66,273	120,364
32	--	2884	9,167	31,218	69,775	--	--	--	9,915	31,808	69,185	125,175	291,578	--	10,124	29,883	68,055	124,117
33	--	3022	9,462	32,182	71,610	--	--	--	10,278	32,716	71,403	127,791	297,822	--	10,498	30,879	69,973	126,880
34	--	3142	9,790	33,136	73,753	--	--	--	10,659	33,656	73,159	130,004	304,175	--	10,875	31,665	72,248	130,350
35	--	3244	10,089	34,078	75,385	--	--	--	11,037	34,643	74,930	133,929	310,067	--	11,240	32,446	74,206	133,748
36	--	3364	10,362	34,892	77,290	--	--	--	11,359	35,457	76,877	137,124	316,720	--	11,598	[illegible]	76,318	137,229
37	--	3462	10,597	35,873	79,134	--	--	--	--	36,436	78,923	140,366	322,959	--	--	34,320	78,571	140,124
38	--	3556	10,844	36,898	81,105	--	--	--	--	37,349	80,936	143,589	330,426	--	--	35,275	80,612	143,160
39	--	3676	11,152	37,853	82,790	--	--	--	--	38,436	83,056	146,511	337,743	--	--	36,337	82,874	146,232
40	--	3760	11,484	38,887	84,801	--	--	--	--	39,501	85,164	149,960	343,736	--	--	37,459	84,475	149,221
41	--	3858	11,737	39,890	86,693	--	--	--	--	40,401	86,898	153,170	348,730	--	--	38,608	86,605	152,723
42	--	3978	12,025	40,986	88,633	--	--	--	--	41,463	88,792	156,831	353,425	--	--	[illegible]	88,620	155,812
43	--	4080	--	41,976	90,543	--	--	--	--	42,557	90,875	159,909	359,607	--	--	40,739	90,754	158,822
44	--	4191	--	43,107	92,233	--	--	--	--	43,747	92,937	162,903	363,048	--	--	41,809	92,840	161,827
45	--	--	--	44,242	94,072	--	--	--	--	44,931	95,005	165,598	--	--	--	42,999	94,851	165,008
46	--	--	--	45,337	95,792	--	--	--	--	46,151	97,172	168,819	--	--	--	44,218	96,765	167,688
47	--	--	--	46,147	98,080	--	--	--	--	47,262	99,125	171,758	--	--	--	45,463	98,608	170,955
48	--	--	--	47,313	99,743	--	--	--	--	48,182	101,036	174,704	--	--	--	46,471	100,267	174,048
49	--	--	--	48,461	101,323	--	--	--	--	49,293	102,828	177,524	--	--	--	47,463	102,286	176,811
50	--	--	--	49,619	102,784	--	--	--	--	50,294	104,779	180,514	--	--	--	48,508	104,099	179,693
51	--	--	--	50,639	104,214	--	--	--	--	51,216	106,651	183,658	--	--	--	49,425	105,837	182,688
52	--	--	--	51,731	105,815	--	--	--	--	52,305	108,755	187,281	--	--	--	50,479	108,121	185,924
53	--	--	--	52,892	107,179	--	--	--	--	53,306	110,770	190,933	--	--	--	51,429	110,316	189,333
54	--	--	--	54,094	108,860	--	--	--	--	54,382	112,554	194,136	--	--	--	52,686	112,367	192,200
55	--	--	--	55,066	110,219	--	--	--	--	55,460	114,435	197,502	--	--	--	53,829	112,476	195,577
56	--	--	--	56,065	112,085	--	--	--	--	56,408	116,531	200,677	--	--	--	54,841	116,136	198,822
57	--	--	--	57,125	113,862	--	--	--	--	57,380	118,665	204,552	--	--	--	55,889	118,249	202,360
58	--	--	--	58,119	116,181	--	--	--	--	58,370	120,665	207,809	--	--	--	57,026	120,005	205,889
59	--	--	--	59,052	117,981	--	--	--	--	59,266	122,808	211,597	--	--	--	58,124	122,095	209,536
60	--	--	--	60,007	119,992	--	--	--	--	60,284	125,375	215,195	--	--	--	59,180	123,938	213,314
61	--	--	--	60,966	121,400	--	--	--	--	--	--	--	--	--	--	60,014	--	--
62	--	--	--	62,013	123,472	--	--	--	--	--	--	--	--	--	--	60,960	--	--
63	--	--	--	63,157	125,747	--	--	--	--	--	--	--	--	--	--	61,853	--	--
64	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	62,963	--	--
								Test Series 3, Mortar Sand										
1	--	--	--	--	--	--	--	59	411	2,000	3,744	6,600	12,507	56	348	2,096	4,665	6,778
2	--	--	--	--	--	--	--	70	482	2,668	5,408	10,039	22,515	70	428	2,595	6,361	9,810
3	--	--	--	--	--	--	--	90	568	3,277	7,247	13,735	32,036	95	522	3,238	8,086	13,158
4	--	--	--	--	--	--	--	117	649	3,725	8,615	16,687	40,016	117	619	3,722	9,453	16,513
5	--	--	--	--	--	--	--	139	755	4,180	9,632	19,340	47,707	142	720	4,143	10,504	18,553
6	--	--	--	--	--	--	--	165	843	4,523	10,417	21,709	55,176	170	821	4,584	11,538	21,435

(Continued)

Table 1 (Continued)

Depth of Penetration cm	Point Force, N Plates, cm Diam 2.54	5.08	10.16	20.32	30.48	40.64	50.96	Smooth-Walled Cylinders, cm Diam 5.08	10.16	20.32	30.48	40.64	50.96	Rough-Walled Cylinders, cm Diam 5.08	10.16	20.32	30.48	40.64
Test Series 3, Mortar Sand (Continued)																		
7	--	--	--	--	--	--	--	189	935	4,874	11,444	24,119	61,835	195	914	4,849	12,393	23,384
8	--	--	--	--	--	--	--	213	1,032	5,273	12,078	25,832	67,351	230	1,012	5,237	13,194	25,342
9	--	--	--	--	--	--	--	235	1,137	5,751	13,165	27,865	72,248	260	1,104	5,633	14,008	27,040
10	--	--	--	--	--	--	--	266	1,232	6,065	13,600	29,269	76,602	292	1,203	6,361	14,716	28,734
11	--	--	--	--	--	--	--	284	1,320	6,455	14,417	31,123	80,262	320	1,295	6,704	15,640	29,929
12	--	--	--	--	--	--	--	310	1,419	6,696	15,301	32,734	84,304	352	1,396	7,117	16,410	31,992
13	--	--	--	--	--	--	--	343	1,514	7,064	16,311	34,294	87,793	390	1,503	7,530	17,358	33,323
14	--	--	--	--	--	--	--	365	1,595	7,475	16,947	35,845	91,111	425	1,600	7,899	17,952	35,033
15	--	--	--	--	--	--	--	396	1,692	7,926	17,648	37,180	94,815	461	1,703	8,335	18,827	36,427
16	--	--	--	--	--	--	--	427	1,786	8,355	18,643	39,294	98,263	490	1,801	9,680	19,655	38,232
17	--	--	--	--	--	--	--	460	1,877	8,658	19,334	41,039	101,816	524	1,917	9,182	20,709	39,974
18	--	--	--	--	--	--	--	486	1,973	9,047	20,286	42,752	105,879	557	2,008	9,577	21,667	41,804
19	--	--	--	--	--	--	--	513	2,079	9,434	21,056	44,240	109,593	590	2,125	10,018	22,336	43,938
20	--	--	--	--	--	--	--	546	2,182	9,909	21,804	45,813	113,[illegible]68	622	2,218	10,449	23,106	45,439
21	--	--	--	--	--	--	--	568	2,275	10,355	22,629	47,430	118,159	656	2,332	10,812	24,168	46,807
22	--	--	--	--	--	--	--	594	2,365	10,792	23,342	49,044	121,569	689	2,435	11,156	25,092	48,624
23	--	--	--	--	--	--	--	623	2,451	11,148	24,218	50,937	125,155	725	2,555	11,533	26,121	50,404
24	--	--	--	--	--	--	--	647	2,554	11,599	25,131	52,182	128,981	749	2,663	12,000	26,956	52,149
25	--	--	--	--	--	--	--	671	2,647	11,975	25,938	53,777	131,896	777	2,772	12,485	27,934	53,029
26	--	--	--	--	--	--	--	689	2,759	12,429	26,662	55,495	135,262	802	2,885	12,899	28,856	55,625
27	--	--	--	--	--	--	--	704	2,842	12,854	27,581	57,464	139,367	827	3,001	13,413	29,725	57,374
28	--	--	--	--	--	--	--	722	2,944	13,190	28,367	59,112	143,455	854	3,105	13,814	30,587	59,255
29	--	--	--	--	--	--	--	737	3,056	13,623	29,234	60,988	147,001	880	3,222	14,326	31,494	60,753
30	--	--	--	--	--	--	--	752	3,159	14,116	29,858	62,440	150,519	906	3,322	14,576	32,378	62,504
31	--	--	--	--	--	--	--	774	3,256	14,510	30,776	63,879	154,508	940	3,439	15,191	33,476	64,194
32	--	--	--	--	--	--	--	788	3,364	14,869	31,746	65,852	157,471	968	3,558	15,558	34,439	66,053
33	--	--	--	--	--	--	--	814	3,483	15,328	32,732	68,015	160,903	994	3,681	16,049	35,341	67,969
34	--	--	--	--	--	--	--	836	3,582	15,794	33,614	69,524	164,610	1,022	3,794	16,534	36,251	69,423
35	--	--	--	--	--	--	--	856	3,687	16,248	34,300	71,258	168,326	1,046	3,924	16,877	37,253	71,082
36	--	--	--	--	--	--	--	876	3,782	16,667	35,222	73,009	172,092	1,075	4,013	17,216	38,170	72,895
37	--	--	--	--	--	--	--	898	3,885	17,154	36,108	74,254	175,852	1,094	4,118	17,654	39,070	74,934
38	--	--	--	--	--	--	--	911	3,978	17,510	37,098	76,188	179,244	1,121	4,228	18,096	39,943	76,859
39	--	--	--	--	--	--	--	939	4,092	17,953	37,926	77,937	182,934	1,151	4,347	18,519	40,926	78,422
40	--	--	--	--	--	--	--	957	4,187	18,374	38,795	79,770	186,390	1,178	4,453	18,996	42,159	80,150
41	--	--	--	--	--	--	--	977	4,272	18,852	39,642	81,061	189,910	1,206	4,555	19,433	43,167	81,681
42	--	--	--	--	--	--	--	999	4,365	19,265	40,555	83,032	194,240	1,238	4,665	19,975	44,019	83,547
43	--	--	--	--	--	--	--	1019	4,457	19,863	41,373	84,920	198,092	1,267	4,774	20,420	45,103	85,503
44	--	--	--	--	--	--	--	1043	4,554	20,285	42,418	86,889	202,421	1,295	4,881	20,878	46,046	87,232
45	--	--	--	--	--	--	--	1065	4,651	20,727	43,269	88,463	206,415	1,324	4,990	21,424	47,140	88,653
46	--	--	--	--	--	--	--	1093	4,754	21,163	44,154	90,173	209,637	1,349	5,095	21,970	48,131	90,354
47	--	--	--	--	--	--	--	--	4,844	21,522	45,082	91,698	212,388	--	5,215	22,497	49,108	92,336
48	--	--	--	--	--	--	--	--	4,952	22,053	46,015	93,841	215,800	--	5,334	22,953	50,180	94,257
49	--	--	--	--	--	--	--	--	--	22,598	46,853	95,643	--	--	--	23,342	51,321	95,592
50	--	--	--	--	--	--	--	--	--	22,958	47,630	97,559	--	--	--	23,861	52,322	97,662
51	--	--	--	--	--	--	--	--	--	23,356	48,953	99,094	--	--	--	24,248	53,096	99,266
52	--	--	--	--	--	--	--	--	--	23,769	49,522	101,215	--	--	--	24,723	54,412	101,246
53	--	--	--	--	--	--	--	--	--	24,302	50,580	103,404	--	--	--	25,183	55,578	103,094
54	--	--	--	--	--	--	--	--	--	24,767	51,218	105,081	--	--	--	25,626	56,538	104,687
55	--	--	--	--	--	--	--	--	--	25,225	52,250	107,223	--	--	--	26,069	57,503	106,706
56	--	--	--	--	--	--	--	--	--	25,646	53,097	108,539	--	--	--	26,609	58,638	108,332
57	--	--	--	--	--	--	--	--	--	26,026	54,045	110,853	--	--	--	27,208	59,816	110,624

(Continued)

Table 1 (Continued)

Depth of Penetration cm	Point Force, N																	
	Plates, cm Diam							Smooth-Walled Cylinders, cm Diam						Rough-Walled Cylinders, cm Diam				
	2.54	5.08	10.16	20.32	30.48	40.64	60.96	5.08	10.16	20.32	30.48	40.64	60.96	5.08	10.16	20.32	30.48	40.64
Test Series 3, Mortar Sand (Continued)																		
58	--	--	--	--	--	--	--	--	--	26,563	55,009	112,538	--	--	--	27,771	60,907	112,030
59	--	--	--	--	--	--	--	--	--	27,045	55,860	114,102	--	--	--	28,280	62,056	114,274
60	--	--	--	--	--	--	--	--	--	27,560	56,749	115,797	--	--	--	28,824	63,150	115,832
61	--	--	--	--	--	--	--	--	--	27,944	57,750	177,423	--	--	--	29,224	64,245	117,389
62	--	--	--	--	--	--	--	--	--	--	58,687	119,528	--	--	--	[illegible]	65,300	120,166
63	--	--	--	--	--	--	--	--	--	--	59,481	121,611	--	--	--	30,389	66,215	122,135
64	--	--	--	--	--	--	--	--	--	--	60,517	123,435	--	--	--	--	67,494	124,392
65	--	--	--	--	--	--	--	--	--	--	61,479	125,261	--	--	--	--	68,550	122,661
66	--	--	--	--	--	--	--	--	--	--	62,396	127,510	--	--	--	--	--	--
Test Series 5, Mortar Sand																		
1	--	84	1,249	9,648	24,038	--	--	111	1,147	6,199	24,718	39,969	82,774	138	1,311	6,359	17,763	33,326
2	--	116	1,235	10,452	28,686	--	--	124	1,218	9,235	29,010	50,635	113,913	178	1,307	9,261	26,171	47,182
3	--	160	1,240	10,279	30,997	--	--	178	1,347	9,528	30,829	59,407	137,657	222	1,400	9,430	30,281	57,661
4	--	222	1,382	9,688	31,219	--	--	244	1,564	9,399	31,370	63,305	172,943	284	1,564	9,399	30,170	63,340
5	--	280	1,529	9,683	30,184	--	--	284	1,738	9,412	31,366	64,496	189,892	338	1,751	9,537	30,219	64,771
6	--	351	1,751	10,341	30,473	--	--	356	1,906	9,692	31,352	64,007	201,184	413	1,929	9,750	30,401	65,265
7	--	431	1,951	10,817	31,144	--	--	431	2,106	9,812	31,624	63,594	208,988	493	2,186	10,248	31,295	65,793
8	--	502	2,133	11,426	32,197	--	--	493	2,311	10,586	32,583	64,442	209,837	560	2,378	10,839	32,015	66,691
9	--	573	2,351	11,972	33,121	--	--	556	2,533	11,092	33,472	66,784	211,219	649	2,600	11,568	33,130	67,989
10	--	658	2,529	12,594	34,383	--	--	622	2,733	11,812	34,566	69,206	213,947	724	2,822	11,852	34,423	69,540
11	--	720	2,698	13,145	35,654	--	--	693	2,955	12,523	35,823	70,828	218,045	795	3,049	12,372	35,632	71,544
12	--	787	2,937	13,736	37,201	--	--	787	3,204	13,168	37,179	72,433	222,255	889	3,262	12,901	37,276	74,273
13	--	822	3,169	14,559	38,743	--	--	853	3,404	13,679	38,476	74,993	226,880	964	3,502	13,563	38,334	76,157
14	--	933	3,395	15,247	40,249	--	--	924	3,684	14,416	40,276	77,406	230,710	1,053	3,733	14,176	39,912	78,534
15	--	1013	3,617	16,274	41,636	--	--	1009	3,933	15,096	41,649	79,450	235,003	1,142	4,008	15,283	41,383	81,192
16	--	1084	3,844	17,176	43,276	--	--	1093	4,177	15,661	42,938	81,934	238,376	1,227	4,213	15,856	42,525	84,223
17	--	1160	4,080	17,892	44,596	--	--	1169	4,431	16,549	44,538	84,445	243,309	1,315	4,475	16,798	44,391	86,183
18	--	1227	4,253	18,794	46,338	--	--	1253	4,702	17,283	46,133	86,747	248,571	1,418	4,737	17,585	46,120	88,649
19	--	1311	4,484	19,589	48,173	--	--	1333	4,933	18,178	47,769	89,382	253,552	1,502	5,017	18,358	47,800	91,244
20	--	1391	4,773	20,389	49,795	--	--	1404	5,142	18,785	49,386	91,969	259,443	1,582	5,279	19,140	49,275	93,257
21	--	1453	5,000	21,256	51,533	--	--	1489	5,399	19,669	50,742	96,462	264,622	1,658	5,555	19,860	50,790	95,324
22	--	1538	5,244	22,024	53,115	--	--	1569	5,693	20,651	52,381	97,275	270,097	1,760	5,848	20,878	52,635	97,906
23	--	1609	5,497	22,864	54,866	--	--	1644	5,977	21,553	53,981	99,986	275,661	1,853	6,138	21,776	54,639	100,377
24	--	1675	5,795	23,904	56,910	--	--	1729	6,257	22,398	55,510	102,234	280,270	1,951	6,430	22,855	56,052	103,661
25	--	1764	6,031	24,949	58,670	--	--	1827	6,555	23,215	57,141	104,496	286,887	2,053	6,750	23,855	57,625	106,763
26	--	1835	6,310	25,900	60,665	--	--	1924	6,857	23,958	58,754	106,638	292,180	2,160	7,110	24,811	59,470	109,985
27	--	1911	6,582	26,726	62,385	--	--	3027	7,168	24,842	60,327	109,016	298,152	2,271	7,413	25,704	61,309	112,384
28	--	1991	6,888	27,433	63,971	--	--	2138	7,519	25,709	62,074	111,722	303,752	2,400	7,715	26,557	63,403	115,349
29	--	2080	7,177	29,526	65,327	--	--	2249	7,813	26,620	63,811	114,695	309,778	2,529	8,026	27,526	65,131	118,064
30	--	2173	7,466	30,530	66,984	--	--	2360	8,141	27,602	65,367	117,153	316,217	2,662	8,390	28,508	66,536	120,828
31	--	2249	7,701	31,508	70,851	--	--	2475	8,448	28,433	67,011	120,788	320,995	2,795	8,715	29,508	67,984	123,566
32	--	2364	7,977	32,397	72,664	--	--	2595	8,835	29,277	68,784	123,859	327,407	2,946	8,990	30,499	70,140	126,196
33	--	2471	8,261	33,312	74,446	--	--	2729	9,128	30,264	70,562	126,307	333,949	3,066	9,350	31,415	71,788	128,916
34	--	2560	8,546	34,179	76,144	--	--	2858	9,506	31,250	72,277	129,636	339,922	3,213	9,715	32,317	74,099	131,391
35	--	2640	8,844	35,165	78,112	--	--	2978	9,817	32,272	73,588	132,027	--	3,369	10,039	33,357	75,401	134,333
36	--	2720	9,159	36,174	80,028	--	--	3133	10,221	33,134	75,406	135,124	--	3,484	10,372	34,294	77,357	137,733
37	--	2822	9,426	37,152	81,952	--	--	3153	--	34,148	77,463	137,582	--	3,640	10,754	35,228	79,370	141,119
38	--	2924	9,728	38,014	83,916	--	--	3369	--	35,001	79,525	140,537	--	3,813	11,083	36,028	81,467	144,381
39	--	3031	--	39,018	85,645	--	--	3497	--	35,712	81,819	143,275	--	3,942	--	36,850	83,494	147,119
40	--	3115	--	39,907	87,547	--	--	3617	--	36,454	83,272	146,892	--	4,084	--	37,761	85,272	150,087
41	--	3182	--	40,796	89,520	--	--	--	--	37,352	84,592	149,976	--	--	--	38,698	87,214	153,269
42	--	3280	--	41,720	91,222	--	--	--	--	38,307	86,836	153,660	--	--	--	39,698	89,324	156,620

(Continued)

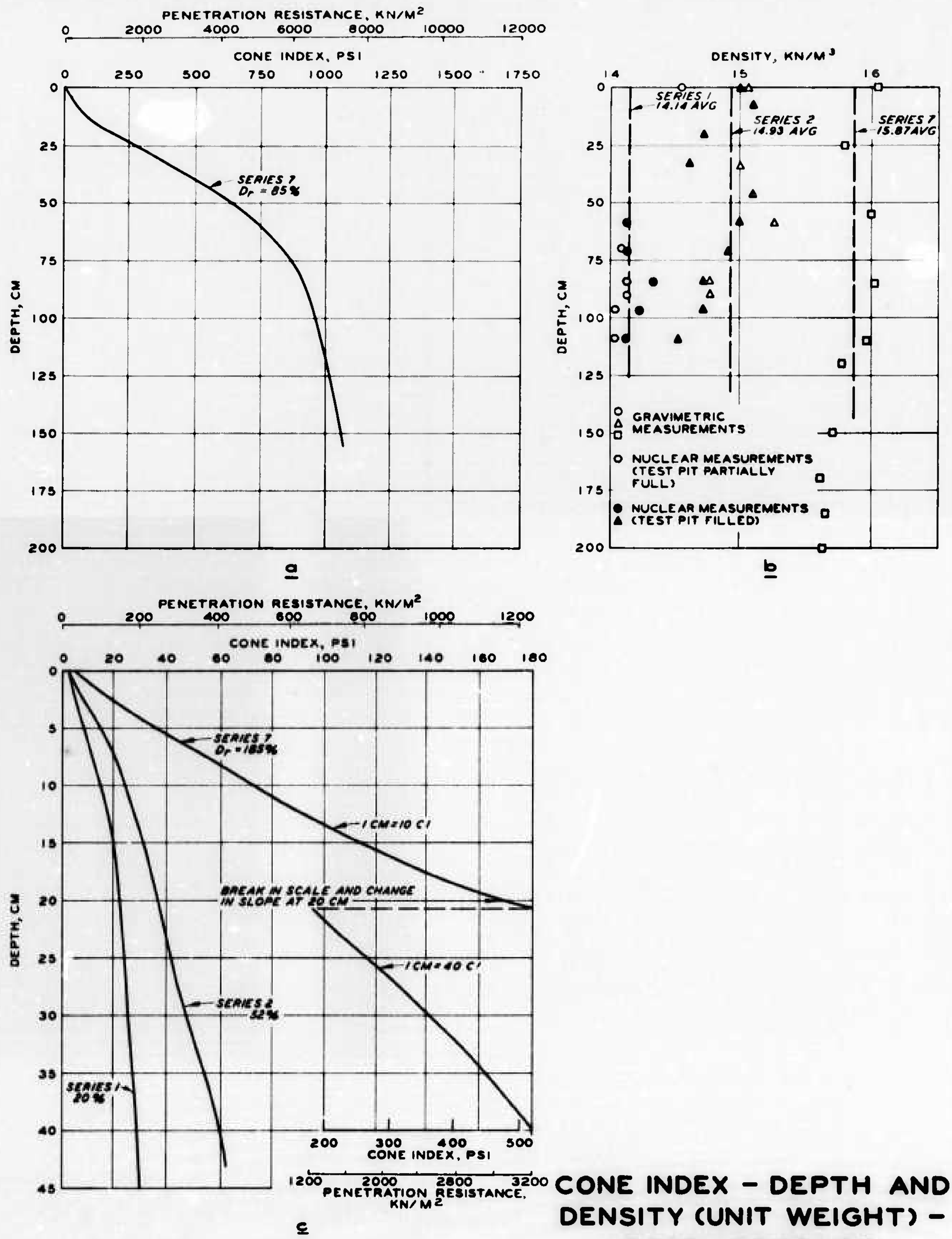
Table 1 (Continued)

Depth of Penetration cm	Point Force, N. Plates, cm Diam 2.54	5.08	10.16	20.32	30.48	40.64	60.96	Smooth-Walled Cylinders, cm Diam 5.08	10.16	20.32	30.48	40.64	60.96	Rough-Walled Cylinders, cm Diam 5.08	10.16	20.32	30.48	40.64
Test Series 5, Mortar Sand (Continued)																		
43	--	3369	--	42,565	93,057	--	--	--	--	39,041	88,391	156,993	--	--	--	40,774	91,431	160,153
44	--	--	--	43,547	94,911	--	--	--	--	39,814	90,311	160,037	--	--	--	41,756	93,120	163,633
45	--	--	--	44,444	96,573	--	--	--	--	40,663	92,657	163,766	--	--	--	42,845	95,550	167,348
46	--	--	--	45,347	98,350	--	--	--	--	41,449	94,639	167,694	--	--	--	43,605	97,275	170,685
47	--	--	--	46,355	100,541	--	--	--	--	42,325	96,257	170,921	--	--	--	44,676	99,292	174,396
48	--	--	--	--	102,292	--	--	--	--	43,262	98,092	174,898	--	--	--	45,964	101,265	176,956
49	--	--	--	--	104,461	--	--	--	--	44,329	99,586	178,427	--	--	--	47,075	103,327	179,244
50	--	--	--	--	106,145	--	--	--	--	45,204	101,674	182,133	--	--	--	48,089	105,825	183,124
51	--	--	--	--	108,225	--	--	--	--	46,070	103,487	185,305	--	--	--	48,902	108,380	186,355
52	--	--	--	--	--	--	--	--	--	47,457	105,794	188,986	--	--	--	49,879	110,504	190,919
53	--	--	--	--	--	--	--	--	--	48,595	107,887	192,225	--	--	--	50,897	112,362	195,625
54	--	--	--	--	--	--	--	--	--	49,466	--	195,745	--	--	--	52,066	114,491	199,687
55	--	--	--	--	--	--	--	--	--	50,324	--	199,033	--	--	--	53,221	116,566	202,500
56	--	--	--	--	--	--	--	--	--	51,506	--	201,962	--	--	--	54,381	118,801	205,148
57	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	208,726
58	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	212,619
59	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	216,832
60	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	220,769
Test Series 6, Mortar Sand																		
1	--	45	186	1,034	2,517	--	--	35	187	1,511	2,773	3,791	9,786	34	194	1,520	1,736	4,226
2	--	60	257	1,478	3,392	--	--	52	242	1,782	3,729	5,361	13,768	51	266	1,778	2,642	5,986
3	--	82	368	1,813	4,448	--	--	78	354	2,200	4,911	7,724	19,162	77	361	2,134	3,780	8,257
4	--	103	444	2,200	5,430	--	--	99	433	2,545	5,928	9,561	23,144	97	449	2,413	4,684	10,329
5	--	122	533	2,508	6,239	--	--	116	513	2,904	6,737	11,211	27,258	121	528	2,717	5,207	11,922
6	--	144	599	2,838	7,115	--	--	137	585	3,219	7,541	12,663	31,218	143	607	2,992	6,270	13,627
7	--	164	671	3,124	7,938	--	--	157	651	3,883	8,328	14,230	34,720	167	697	3,304	7,000	15,286
8	--	185	748	3,392	8,637	--	--	178	733	4,138	9,021	15,521	37,572	189	779	3,584	7,715	16,700
9	--	204	826	3,696	9,359	--	--	198	810	4,440	9,698	17,013	40,871	213	851	3,843	8,485	18,152
10	--	227	902	3,995	10,111	--	--	218	884	4,715	10,399	18,212	43,863	235	935	4,167	9,238	19,523
11	--	243	973	4,290	10,762	--	--	239	966	4,992	11,110	19,516	46,864	262	1,012	4,418	9,966	20,467
12	--	265	1,048	4,576	11,444	--	--	255	1,023	5,311	11,737	20,865	49,874	286	1,093	4,719	10,600	21,633
13	--	286	1,133	4,884	12,214	--	--	276	1,111	5,590	12,505	21,859	53,728	310	1,166	5,016	11,260	22,935
14	--	304	1,199	5,188	12,874	--	--	296	1,203	5,894	13,025	23,043	56,175	354	1,276	5,302	11,814	24,229
15	--	323	1,279	5,491	13,627	--	--	317	1,283	6,241	13,719	24,396	59,074	381	1,368	5,619	12,298	25,436
16	--	340	1,355	5,777	14,322	--	--	333	1,349	6,545	14,470	25,601	62,057	403	1,465	5,889	13,132	26,442
17	--	356	1,435	6,156	15,013	--	--	350	1,459	6,833	15,043	26,950	64,847	427	1,536	6,191	13,946	27,72[illegible]
18	--	371	1,515	6,424	15,721	--	--	366	1,531	7,154	15,474	28,129	67,549	449	1,635	6,521	14,586	28,945
19	--	390	1,586	6,736	16,399	--	--	383	1,584	7,471	16,332	29,262	70,778	473	1,718	6,816	15,275	30,250
20	--	402	1,675	7,044	17,129	--	--	399	1,663	7,78[illegible]	16,896	30,547	73,753	493	1,802	7,130	16,071	31,625
21	--	417	1,750	7,330	17,807	--	--	414	1,758	8,129	17,714	31,730	76,331	517	1,870	7,487	17,596	32,575
22	--	430	1,822	7,647	18,564	--	--	434	1,824	8,494	18,438	33,094	79,451	537	1,962	7,821	18,388	34,063
23	--	440	1,906	7,955	19,334	--	--	446	1,929	8,870	19,371	35,457	82,315	559	2,072	8,173	19,105	35,191
24	--	452	1,977	8,254	20,073	--	--	458	2,011	9,172	19,905	36,606	85,219	579	2,154	8,507	19,864	36,375
25	--	466	2,053	8,558	20,838	--	--	478	2,090	9,524	20,705	37,770	87,841	601	2,242	8,842	20,667	37,719
26	--	475	2,133	8,857	21,578	--	--	493	2,154	9,832	21,460	39,072	90,253	618	2,325	9,154	21,393	39,125
27	--	483	2,204	9,161	22,211	--	--	500	2,242	10,111	22,224	40,339	92,945	636	2,405	9,466	22,139	40,513
28	--	491	2,270	9,469	22,968	--	--	531	2,325	10,404	22,887	41,547	95,629	653	2,486	9,783	22,838	41,758
29	--	500	2,337	9,777	23,720	--	--	543	2,396	10,694	23,642	42,860	98,080	673	2,563	10,113	23,602	42,970
30	--	515	2,408	10,089	24,433	--	--	558	2,462	10,956	24,313	44,150	101,024	595	2,636	10,791	24,250	44,240
31	--	522	2,470	10,380	25,181	--	--	570	2,521	11,271	24,904	45,436	103,919	711	2,717	11,132	25,023	45,379
32	--	528	2,528	10,688	25,898	--	--	585	2,589	11,596	25,5[illegible]1	46,765	106,427	730	2,807	11,482	25,793	46,602
33	--	538	2,604	11,025	26,673	--	--	601	2,65[illegible]	11,972	26,322	48,109	109,080	752	2,902	11,812	26,488	47,982

(Continued)

Table 1 (Concluded)

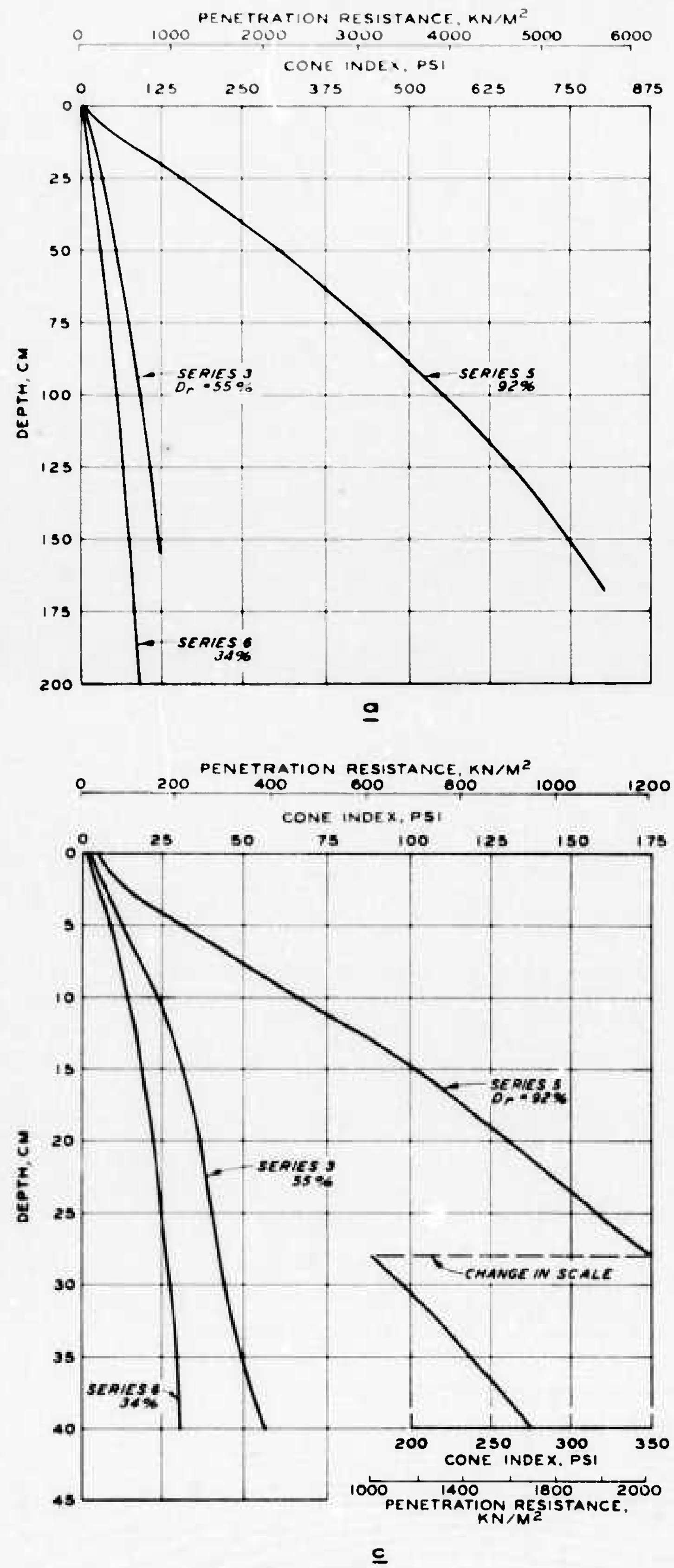
Depth of Penetration cm	Point Force, N																	
	Plates, cm Diam							Smooth-Walled Cylinders, cm Diam						Rough-Walled Cylinders, cm Diam				
	2.54	5.08	10.16	20.32	30.48	40.64	60.96	5.08	10.16	20.32	30.48	40.64	60.96	5.08	10.16	20.32	30.48	40.64
Test Series 6, Mortar Sand (Continued)																		
34	--	550	2,666	11,299	27,355	--	--	613	2,719	12,267	26,931	49,117	111,825	770	2,981	12,181	27,234	49,229
35	--	560	2,724	11,585	28,116	--	--	[illegible]	2,790	12,566	27,628	50,367	114,848	790	3,069	12,536	28,008	50,398
36	--	569	2,786	11,920	28,816	--	--	643	[illegible]	12,925	28,442	51,627	117,919	810	3,150	12,883	28,745	51,823
37	--	575	2,857	12,223	29,845	--	--	658	2,917	13,297	29,233	52,985	120,722	829	3,219	13,242	29,588	53,154
38	--	585	2,906	12,541	30,549	--	--	674	2,994	13,583	29,850	54,267	123,802	847	3,296	13,561	30,417	[illegible]
39	--	598	2,959	12,844	31,337	--	--	689	3,054	[illegible]	30,215	55,587	126,706	865	3,366	13,867	31,198	55,952
40	--	609	3,013	13,147	32,054	--	--	--	3,126	14,214	31,206	56,920	129,716	882	3,425	14,166	31,940	57,360
41	--	613	3,066	13,376	[illegible]	--	--	--	3,181	14,540	32,019	58,089	132,774	--	3,509	14,436	32,773	58,826
42	--	625	3,110	13,688	33,484	--	--	--	--	14,859	33,046	59,387	135,806	--	3,623	14,791	33,662	60,161
43	--	631	3,164	13,983	34,294	--	--	--	--	[illegible]	33,872	60,949	138,952	--	--	15,149	34,503	61,824
44	--	638	3,213	14,278	35,024	--	--	--	--	15,420	34,601	62,381	141,974	--	--	15,534	35,248	63,012
45	--	644	--	14,564	35,807	--	--	--	--	15,752	[illegible]	63,738	144,751	--	--	15,860	36,036	64,517
46	--	645	--	14,876	36,577	--	--	--	--	16,082	[illegible]	65,170	147,892	--	--	16,482	36,988	66,160
47	--	--	--	15,237	37,435	--	--	--	--	16,377	[illegible]	66,532	151,003	--	--	17,120	37,785	67,690
48	--	--	--	15,532	38,192	--	--	--	--	16,691	37,045	67,989	154,228	--	--	17,747	38,504	69,293
49	--	--	--	15,866	38,944	--	--	--	--	16,977	37,943	69,271	157,146	--	--	18,139	39,331	70,868
50	--	--	--	16,148	39,719	--	--	--	--	17,219	38,903	70,708	160,423	--	--	18,865	40,159	72,274
51	--	--	--	16,438	40,471	--	--	--	--	17,457	39,627	72,153	163,504	--	--	19,177	41,741	73,737
52	--	--	--	16,746	41,202	--	--	--	--	17,662	40,680	73,698	166,557	--	--	19,505	42,522	75,145
53	--	--	--	17,050	42,002	--	--	--	--	17,937	41,471	75,200	169,756	--	--	19,835	43,291	76,657
54	--	--	--	17,349	42,799	--	--	--	--	18,225	42,298	76,643	172,488	--	--	20,161	44,064	78,005
55	--	--	--	[illegible]	43,512	--	--	--	--	18,539	42,893	[illegible]	175,665	--	--	20,489	44,798	79,638
56	--	--	--	17,956	44,251	--	--	--	--	18,821	43,538	79,565	178,838	--	--	20,803	45,698	81,059
57	--	--	--	18,247	45,038	--	--	--	--	19,103	44,222	81,051	182,221	--	--	21,129	46,301	82,451
58	--	--	--	18,546	[illegible]	--	--	--	--	19,435	44,920	82,528	185,472	--	--	21,505	47,144	84,108
59	--	--	--	18,823	46,526	--	--	--	--	19,721	45,755	84,150	188,984	--	--	21,853	47,806	85,833
60	--	--	--	19,048	47,353	--	--	--	--	[illegible]	46,546	85,716	191,849	--	--	--	48,558	87,503
61	--	--	--	19,312	48,035	--	--	--	--	20,181	47,138	87,168	195,113	--	--	--	49,350	88,974
62	--	--	--	19,580	48,769	--	--	--	--	20,438	47,951	88,622	198,580	--	--	--	50,140	90,514
63	--	--	--	19,866	49,619	--	--	--	--	20,660	--	90,068	201,625	--	--	--	--	92,338
64	--	--	--	20,152	[illegible]	--	--	--	--	--	--	--	204,864	--	--	--	--	94,131



CONE INDEX – DEPTH AND DENSITY (UNIT WEIGHT) – DEPTH PROFILES

YUMA SAND

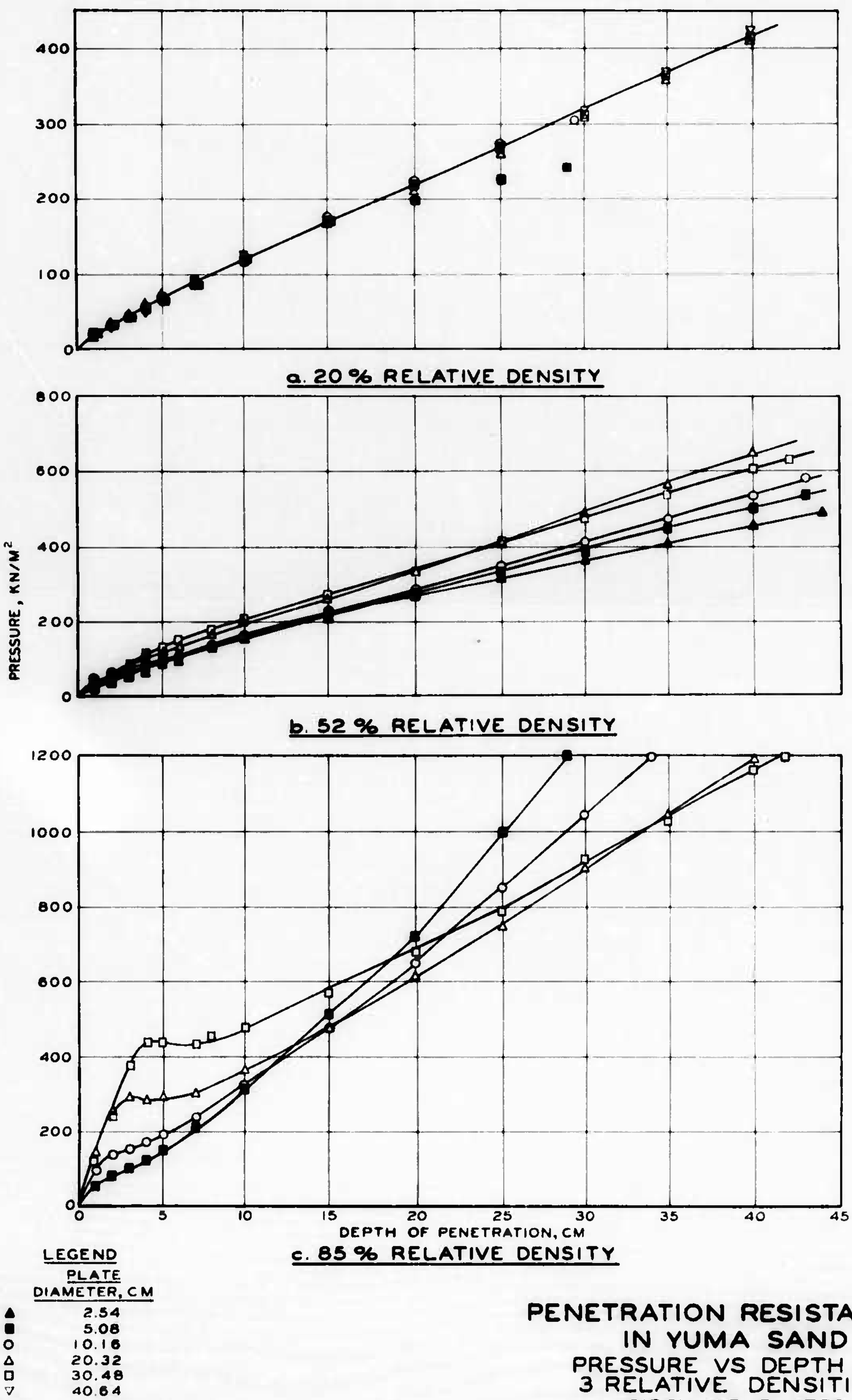
PLATE 1



CONE INDEX - DEPTH AND DENSITY (UNIT WEIGHT) - DEPTH PROFILES

MORTAR SAND

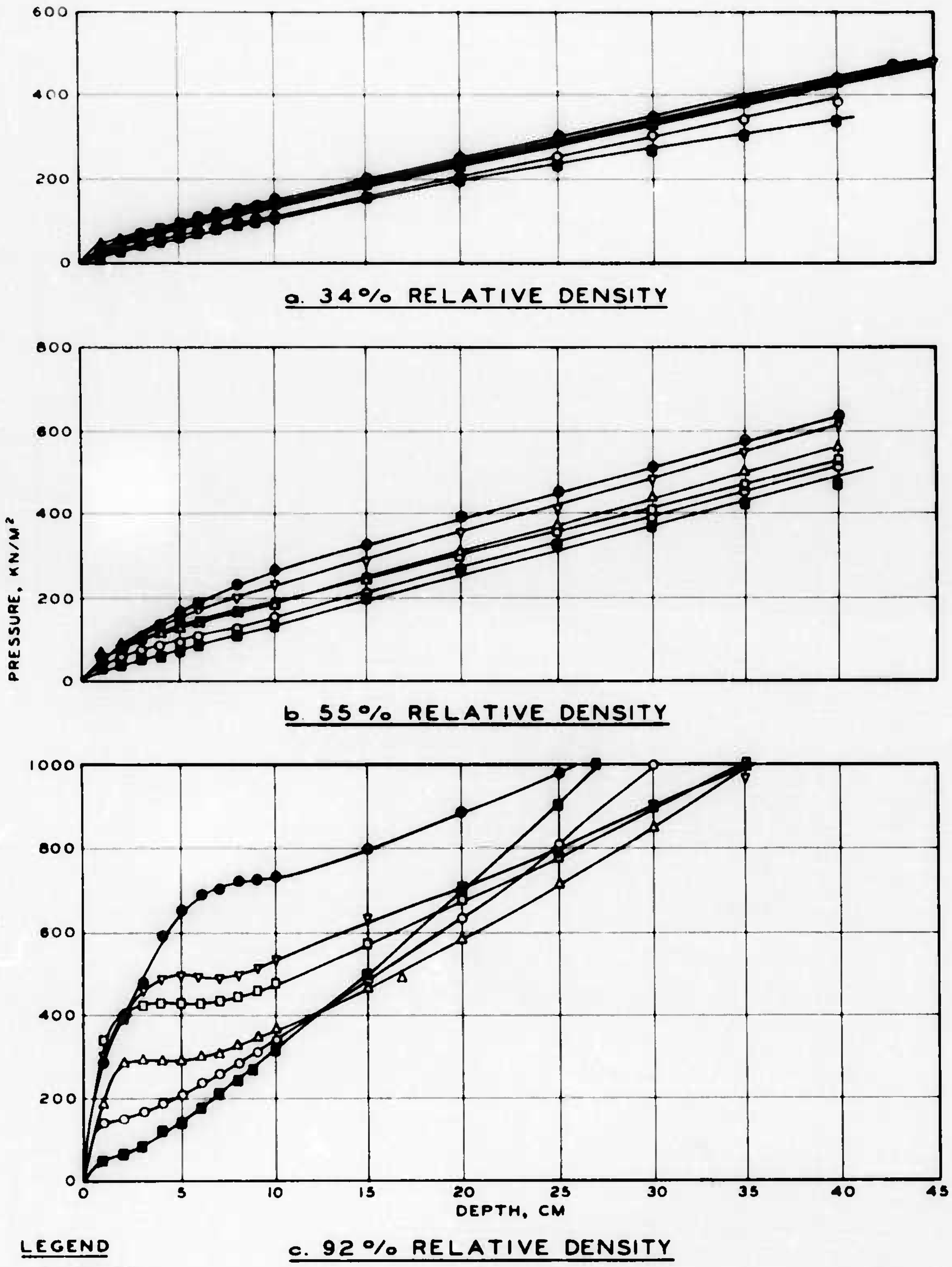
PLATE 2



PENETRATION RESISTANCE IN YUMA SAND

PRESSURE VS DEPTH AT 3 RELATIVE DENSITIES CIRCULAR PLATES

PLATE 3



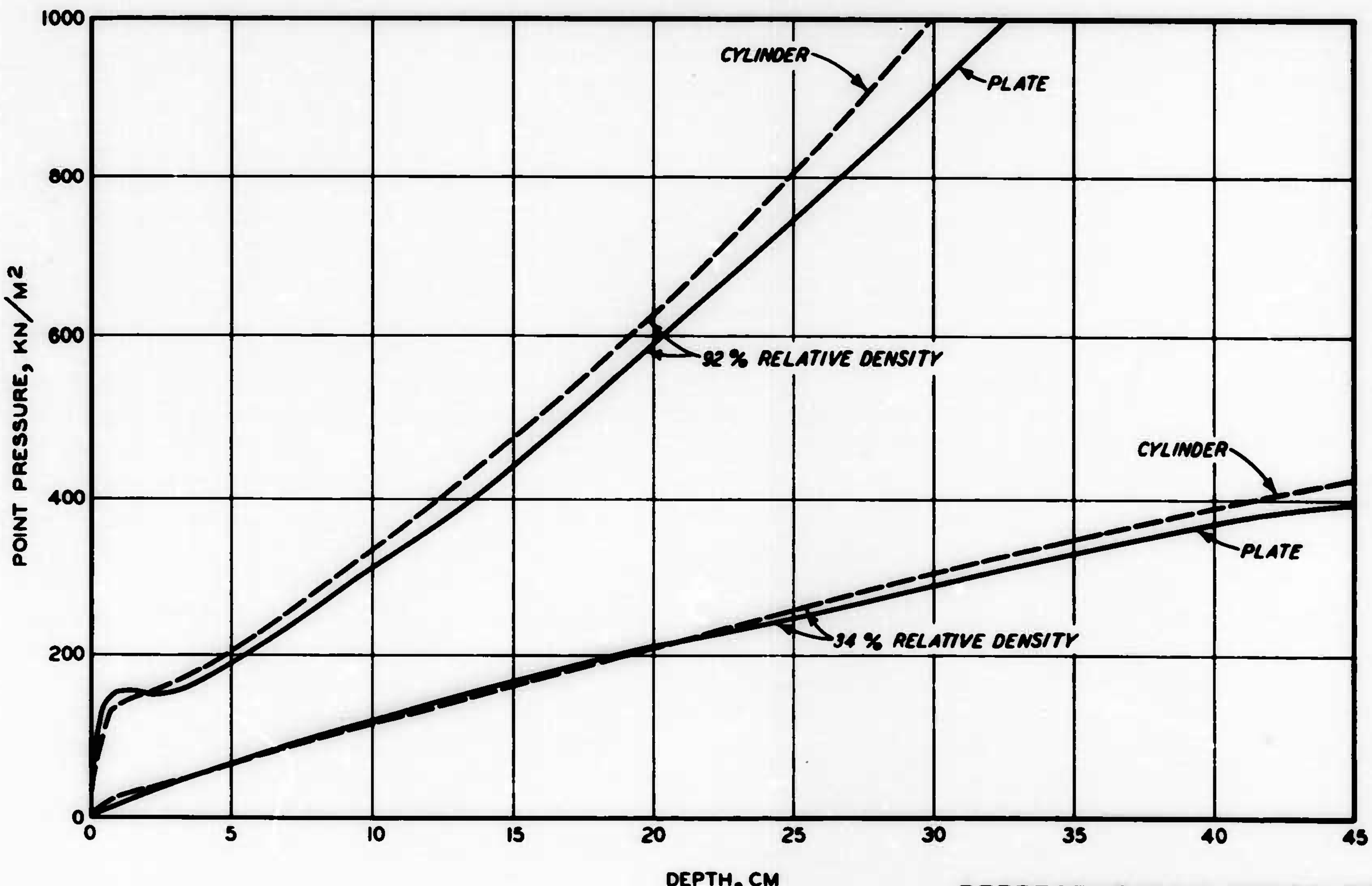
LEGEND

	CYLINDER DIAMETER, CM
■	5.08
○	10.16
△	20.32
□	30.48
▽	40.64
●	60.96

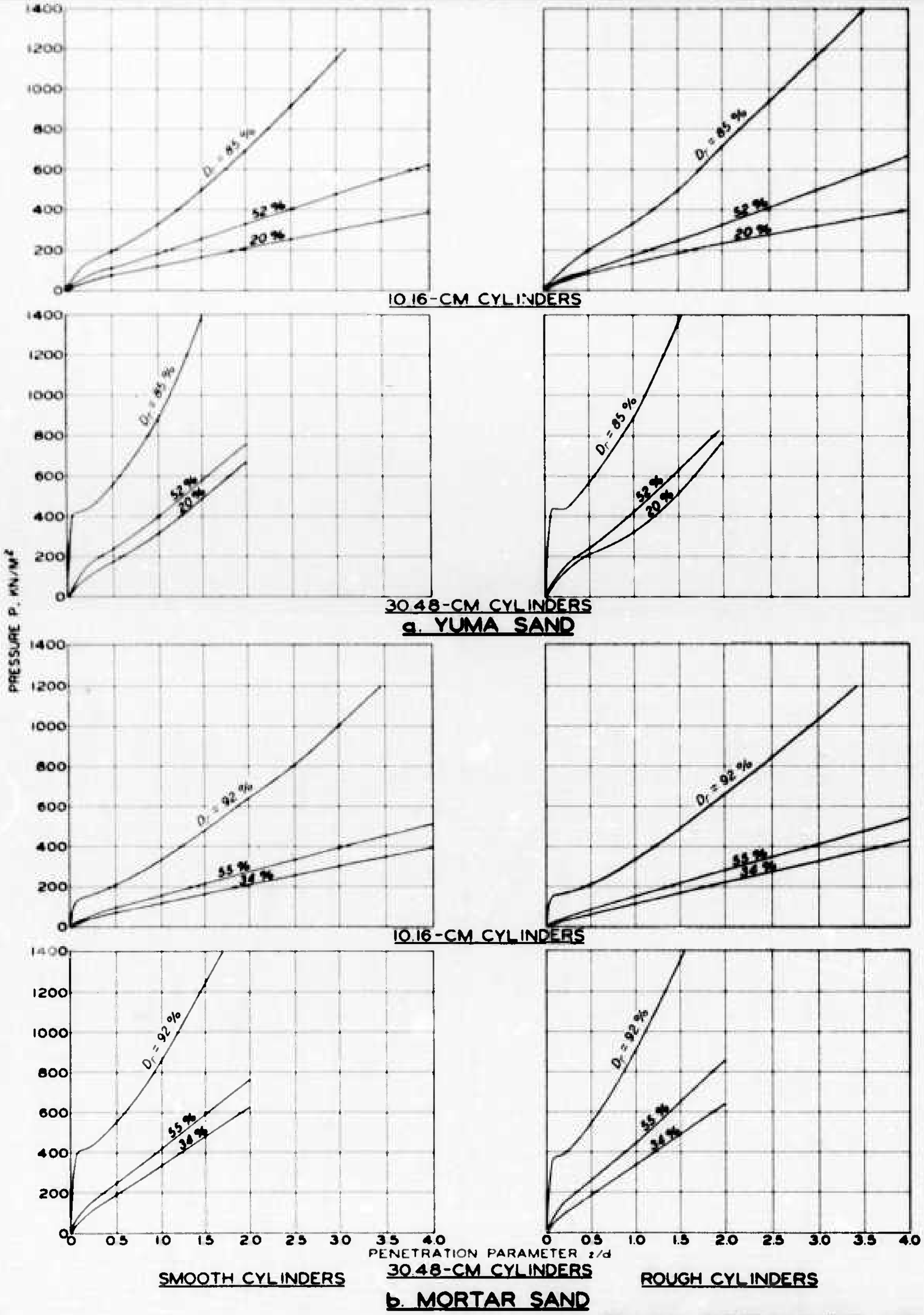
PENETRATION RESISTANCE IN MORTAR SAND

PRESSURE VS DEPTH AT 3 RELATIVE DENSITIES

SMOOTH-WALLED CYLINDERS



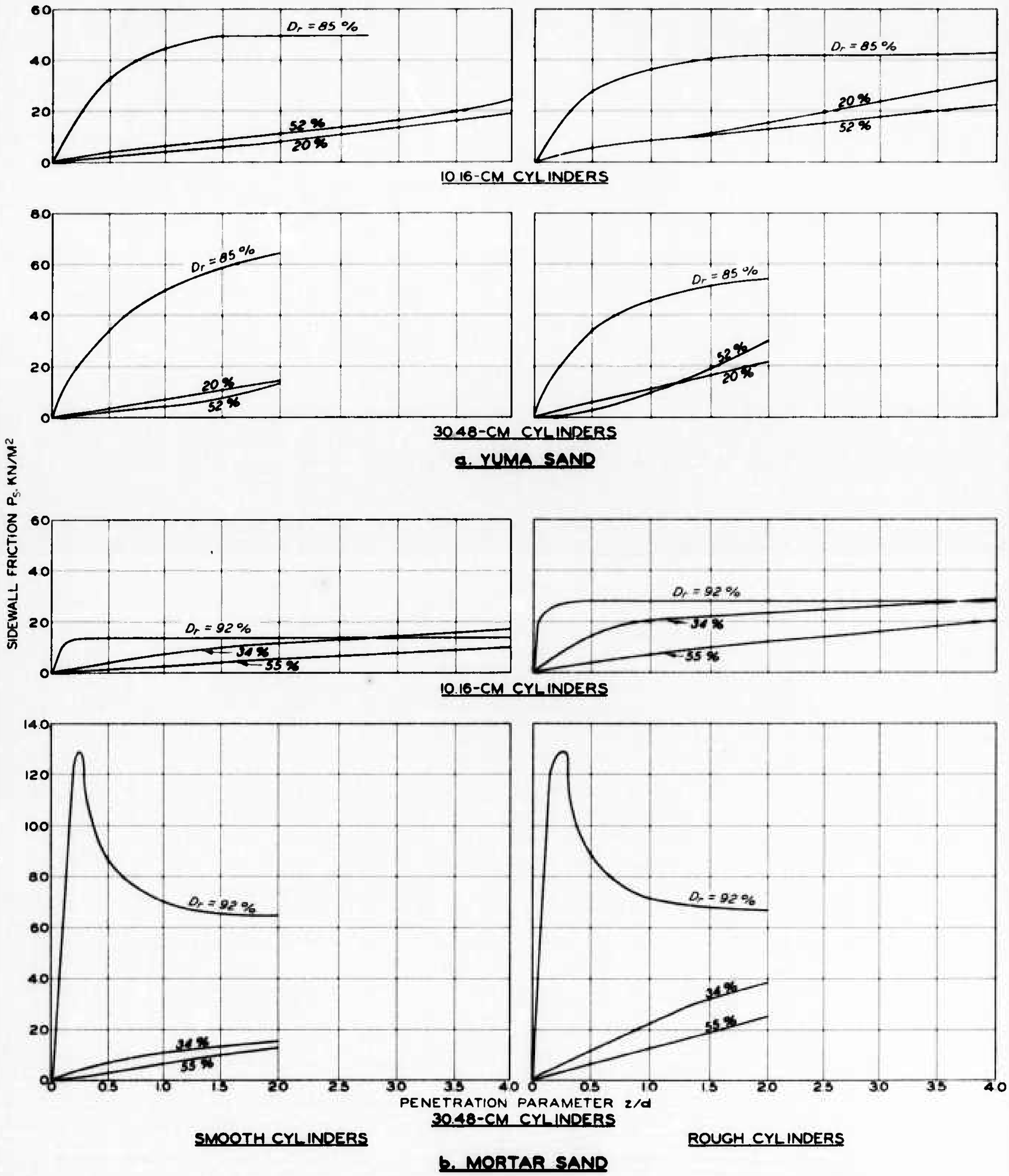
REPRESENTATIVE PRESSURE-DEPTH RELATIONS
10.16-CM-DIAMETER PLATES AND CYLINDERS
MORTAR SAND AT 2 RELATIVE DENSITIES



BASE PRESSURE VS PENETRATION PARAMETER

SMOOTH- AND ROUGH-WALLED CYLINDERS

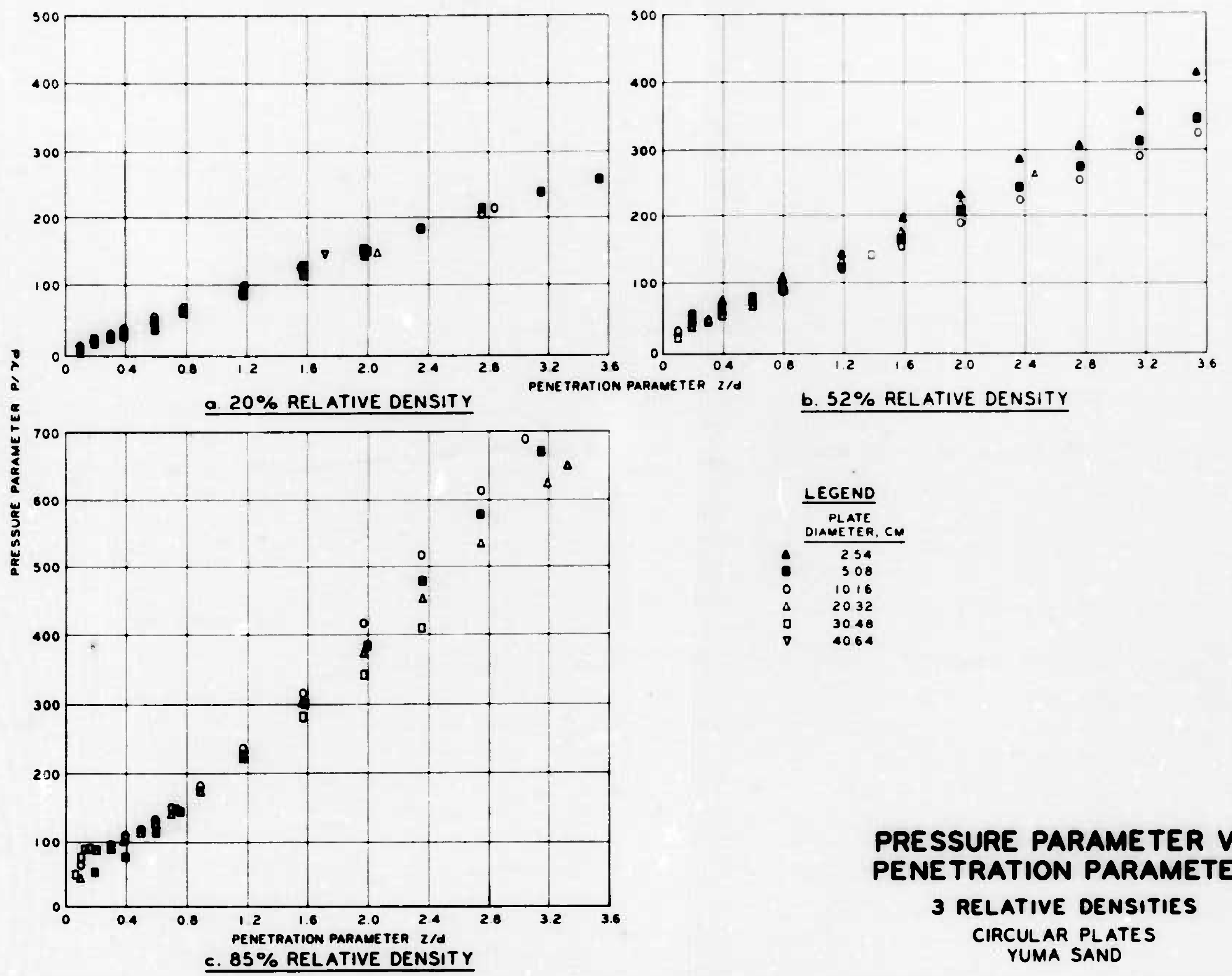
YUMA AND MORTAR SANDS



SIDEWALL FRICTION VS PENETRATION PARAMETER

SMOOTH- AND ROUGH-WALLED CYLINDERS

YUMA AND MORTAR SANDS

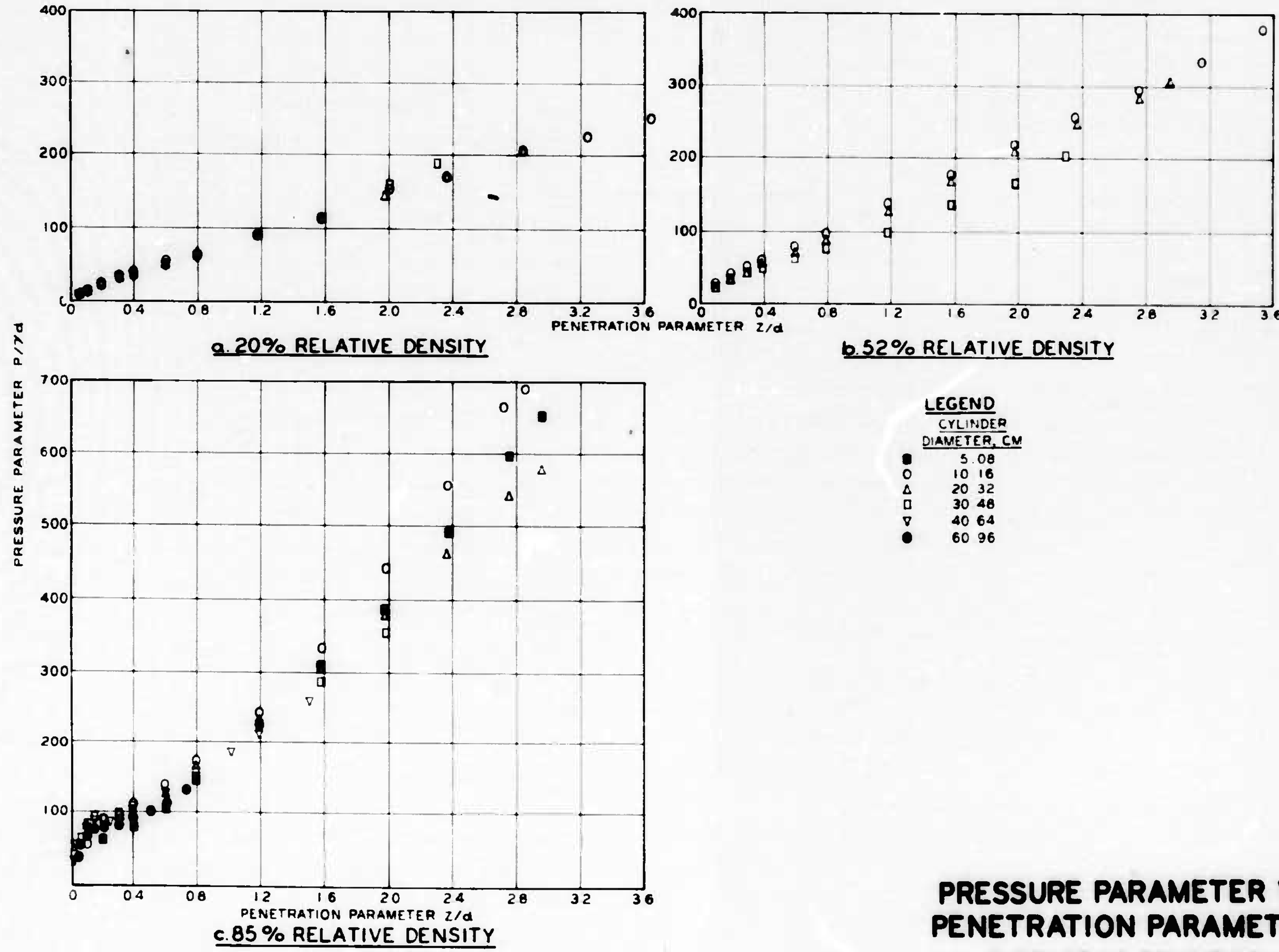


PRESSURE PARAMETER VS PENETRATION PARAMETER

3 RELATIVE DENSITIES

CIRCULAR PLATES
YUMA SAND

PLATE 8

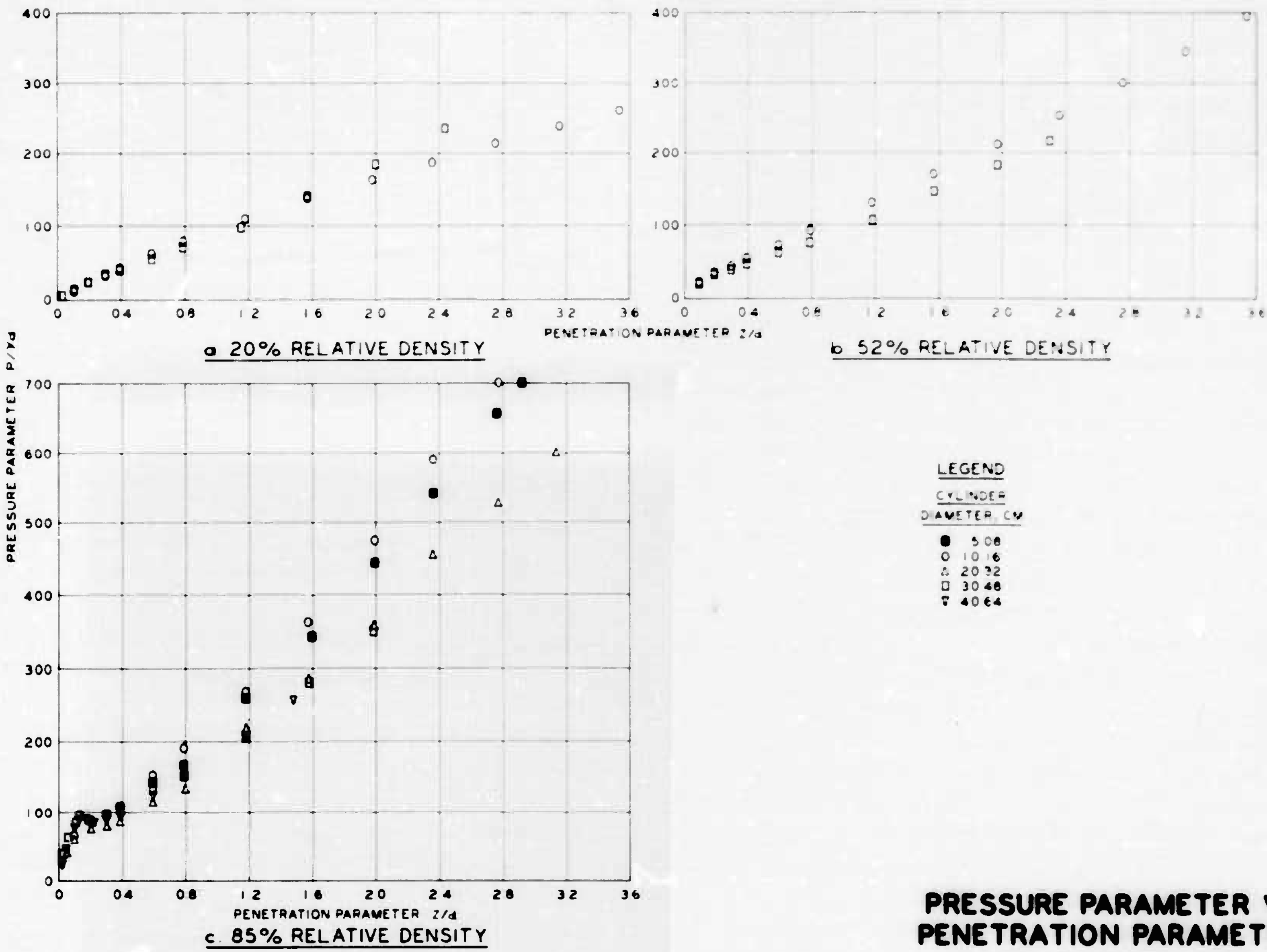


PRESSURE PARAMETER VS PENETRATION PARAMETER

3 RELATIVE DENSITIES

SMOOTH-WALLED CYLINDERS
YUMA SAND

PLATE 9



PRESSURE PARAMETER VS PENETRATION PARAMETER

3 RELATIVE DENSITIES

ROUGH-WALLED CYLINDERS

YUMA SAND

PLATE 10

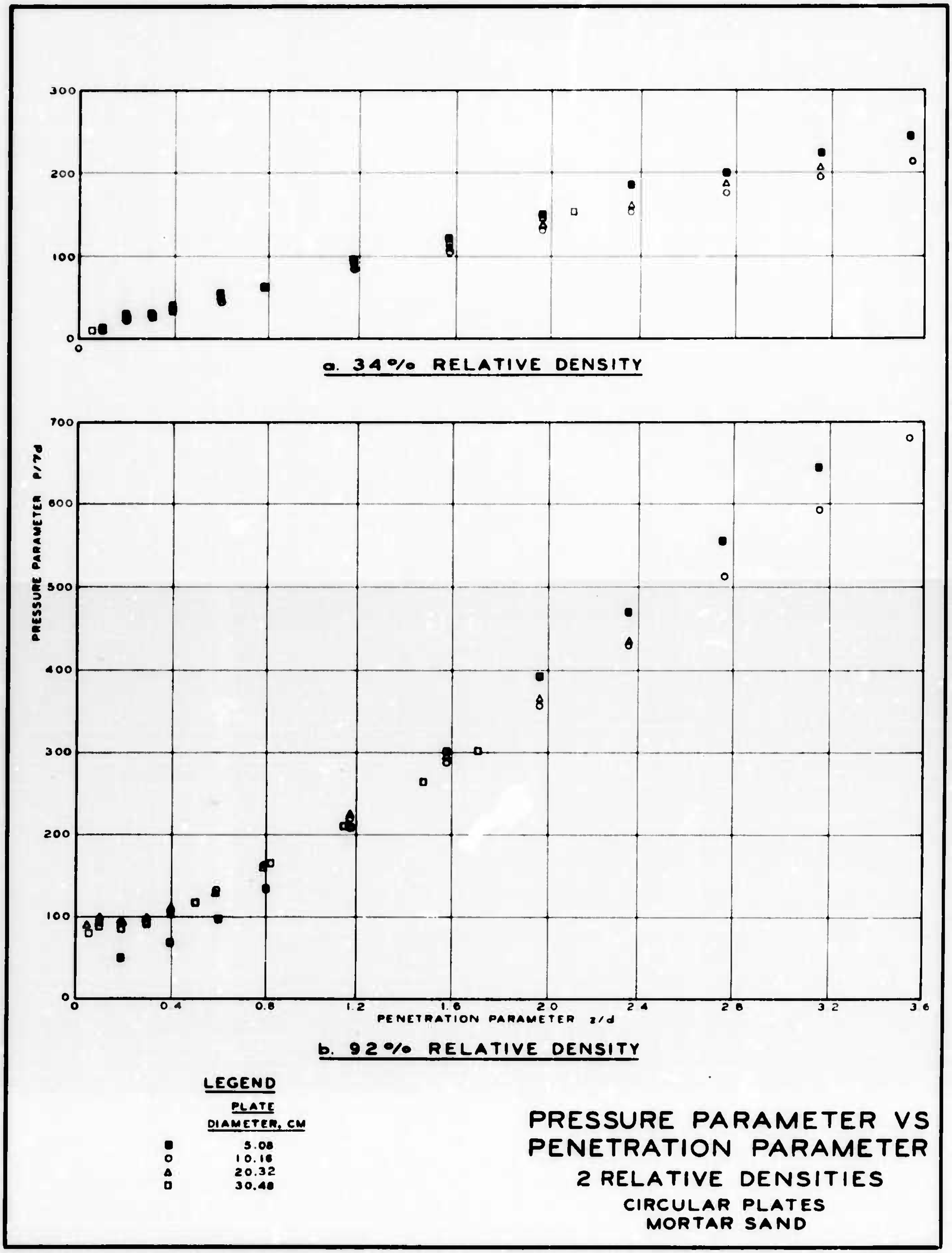
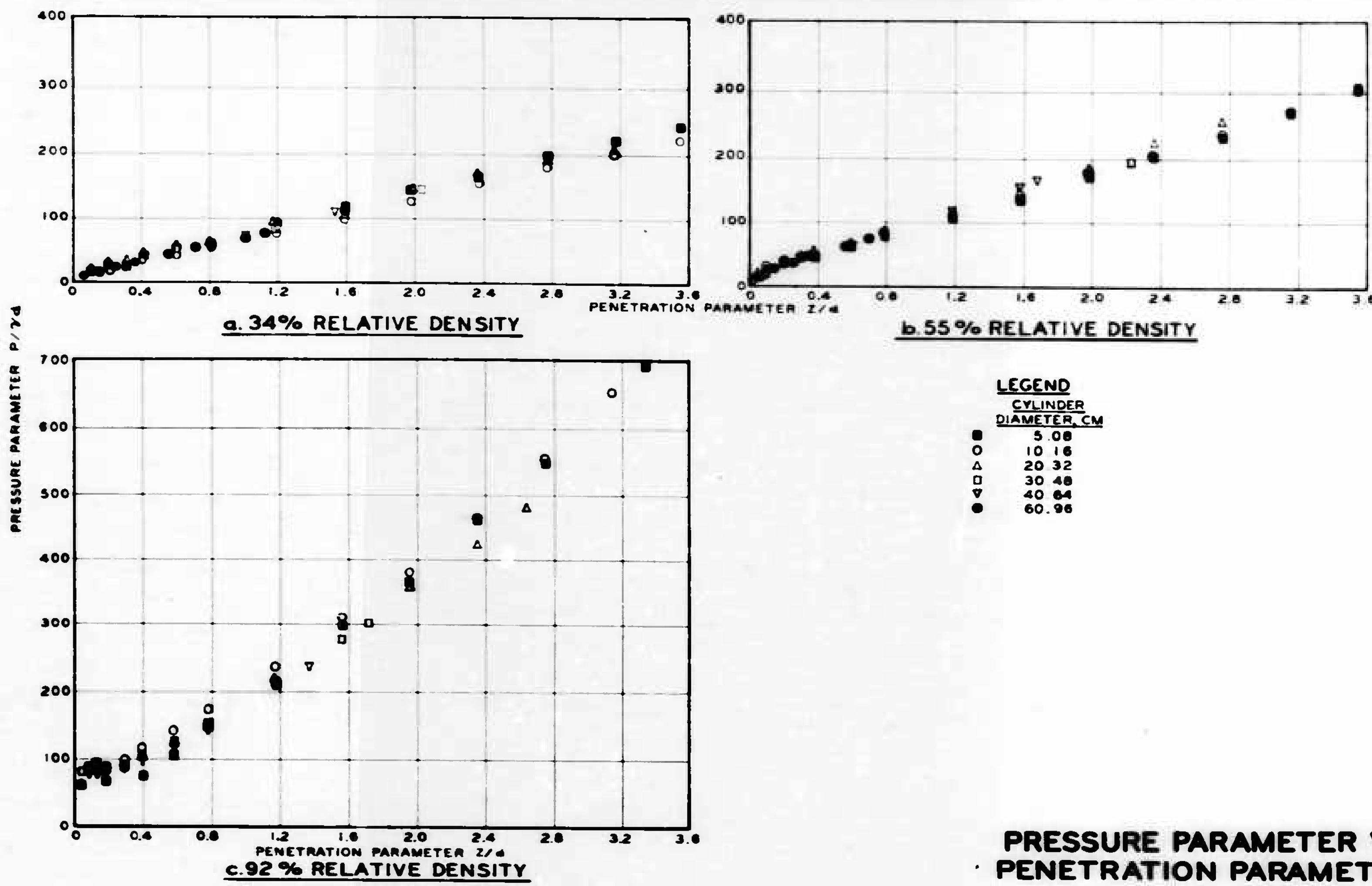

a. 34% RELATIVE DENSITY
PRESSURE PARAMETER p/γd
PENETRATION PARAMETER z/d
b. 92% RELATIVE DENSITY
LEGEND
PLATE DIAMETER, CM
5.08
10.16
20.32
30.48
PRESSURE PARAMETER VS PENETRATION PARAMETER
2 RELATIVE DENSITIES
CIRCULAR PLATES
MORTAR SAND

PLATE 11

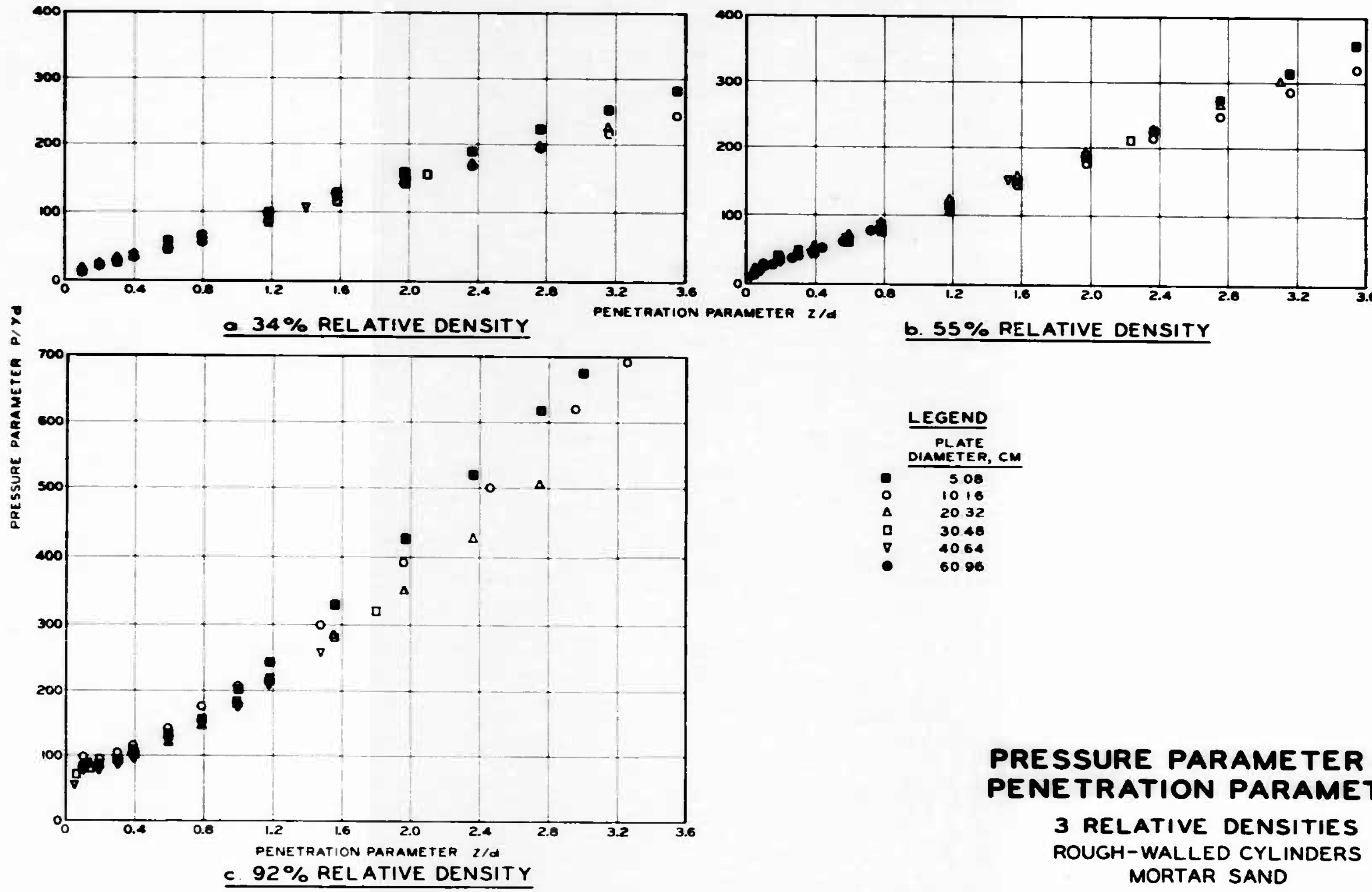


PRESSURE PARAMETER VS PENETRATION PARAMETER

3 RELATIVE DENSITIES

SMOOTH-WALLED CYLINDERS

MORTAR SAND

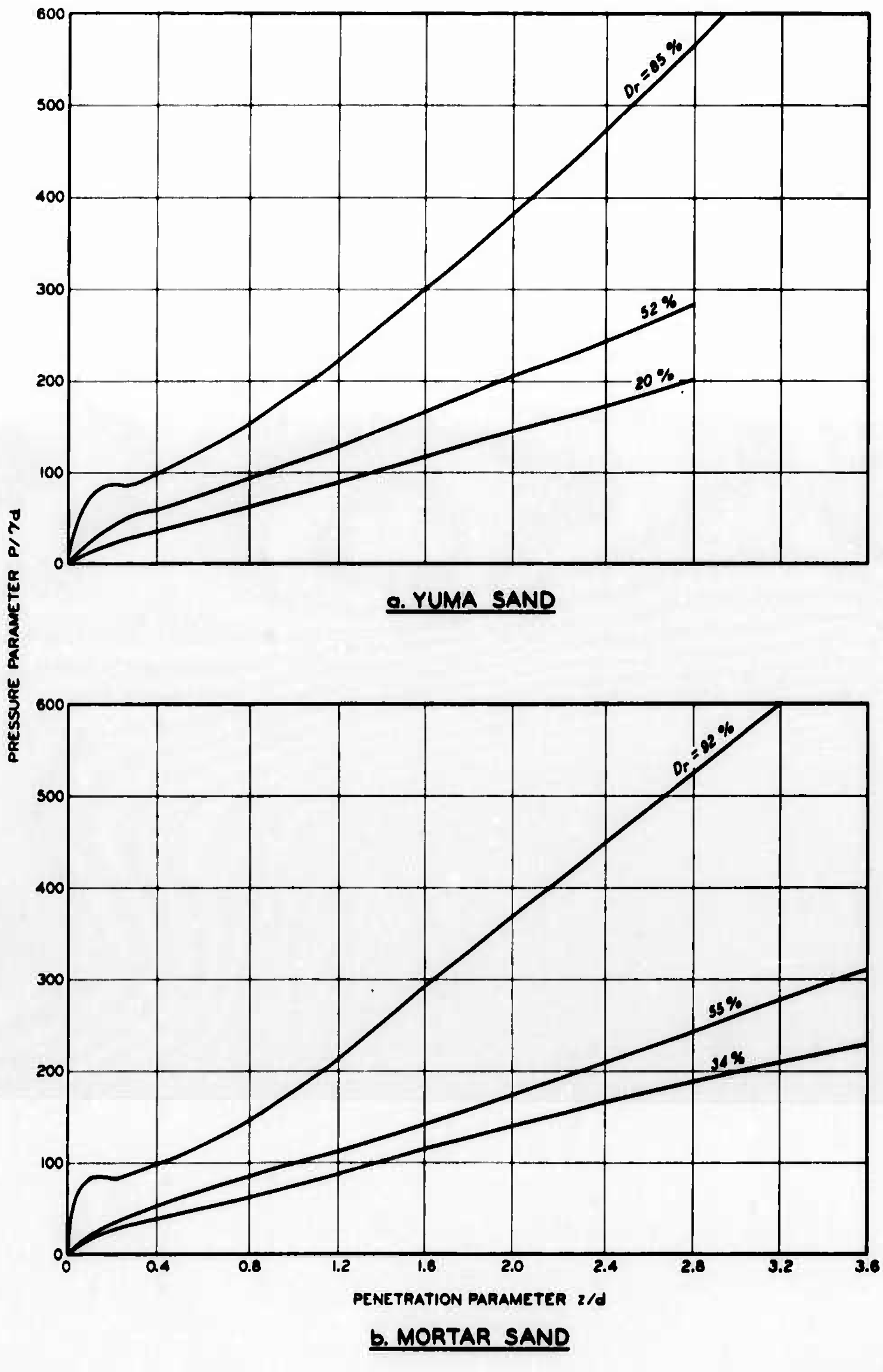


PRESSURE PARAMETER VS PENETRATION PARAMETER

3 RELATIVE DENSITIES

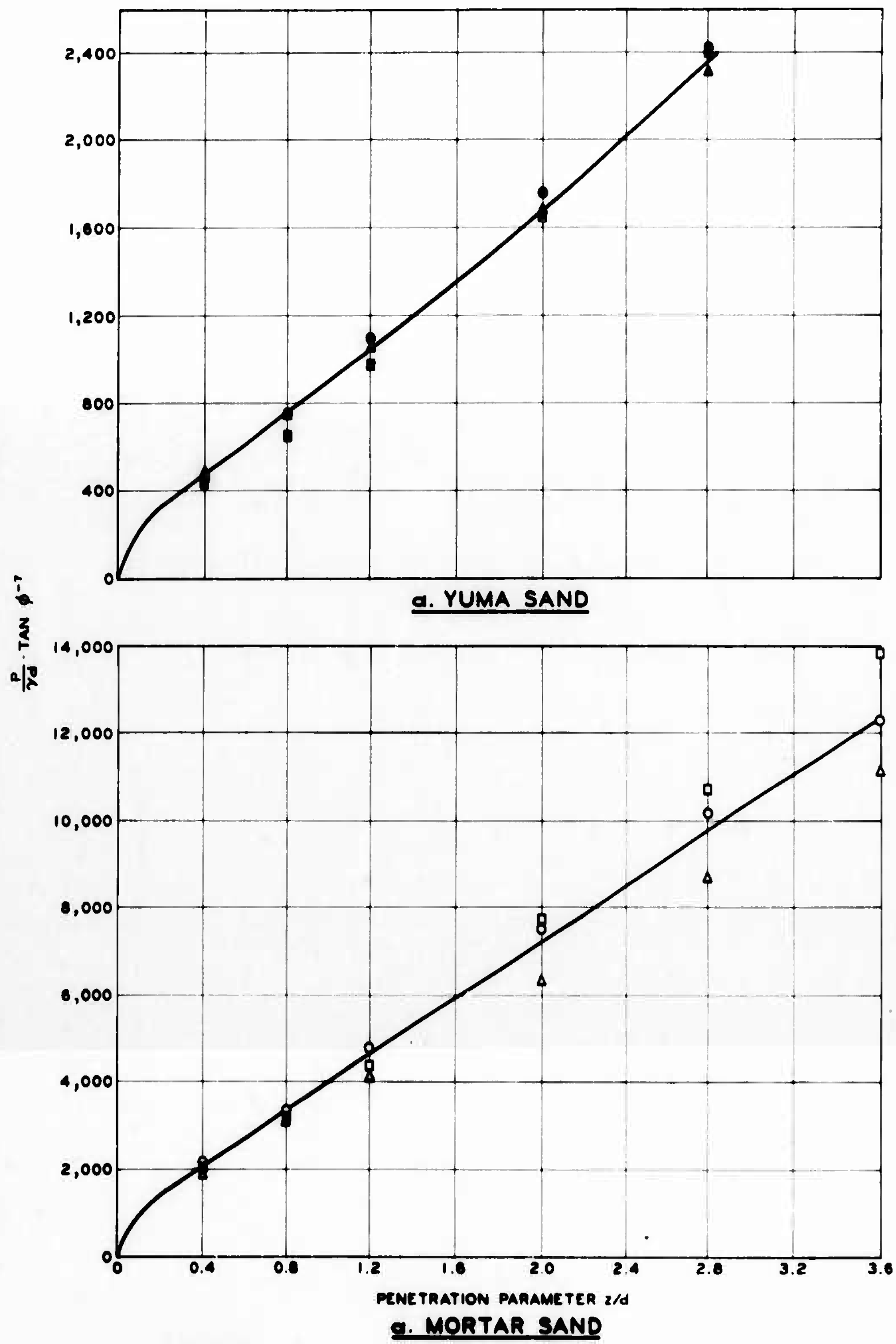
ROUGH-WALLED CYLINDERS

MORTAR SAND



PRESSURE PARAMETER VS PENETRATION PARAMETER

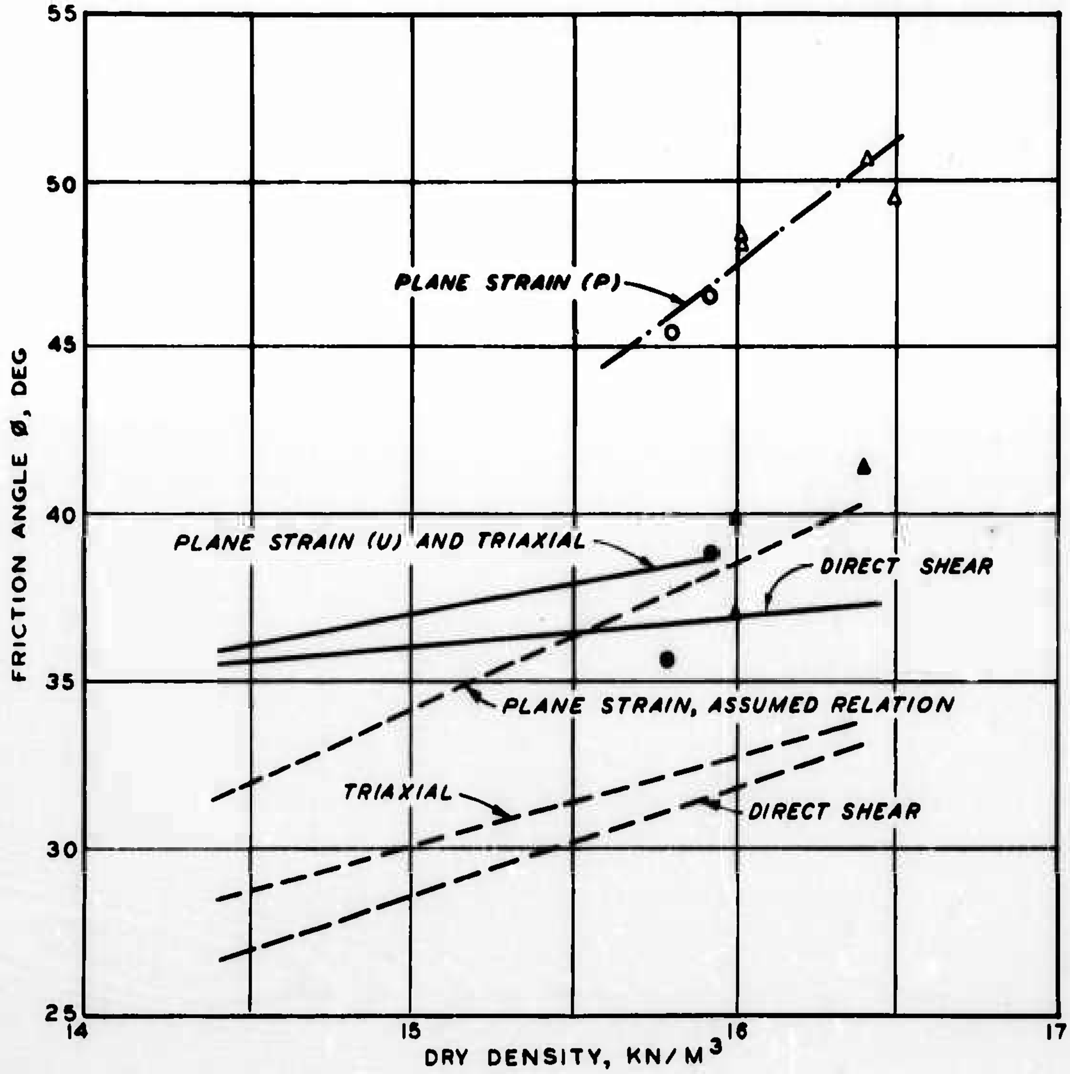
SMOOTH-WALLED CYLINDERS YUMA AND MORTAR SANDS



LEGEND

YUMA SAND	RELATIVE DENSITY, %	MORTAR SAND	RELATIVE DENSITY, %
●	20	○	34
▲	52	△	55
■	85	□	92

EFFECT OF FRICTION ANGLE
YUMA AND MORTAR SANDS

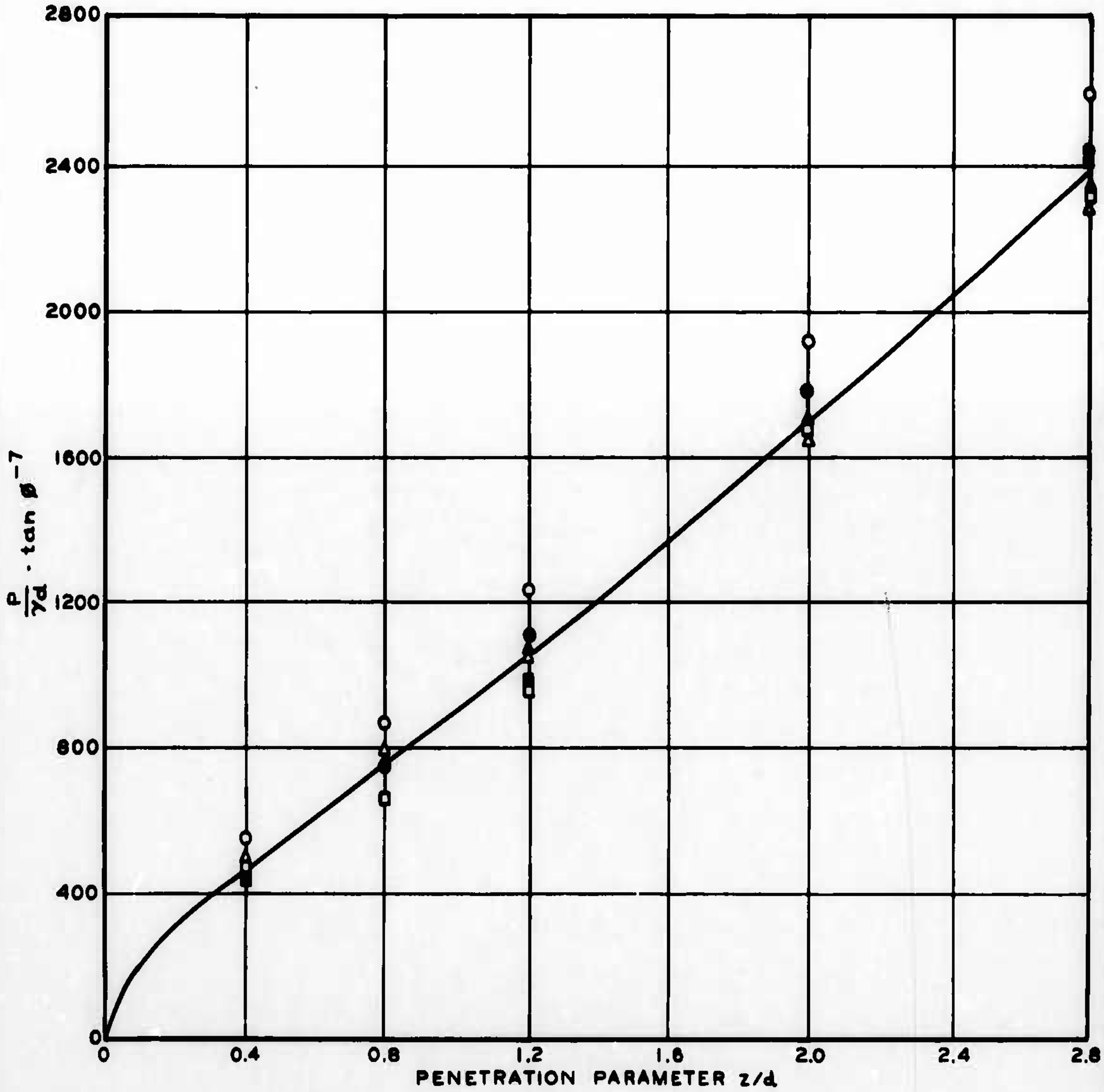


LEGEND

	PLANE STRAIN PEAK Ø	PLANE STRAIN ULTIMATE Ø	
———	○	●	YUMA SAND *
– – –	△	▲	MORTAR SAND *
—·—			BOTH SANDS

NOTE: * AVERAGE OF PUBLISHED AND UNPUBLISHED DATA FROM OTHER SOURCES.

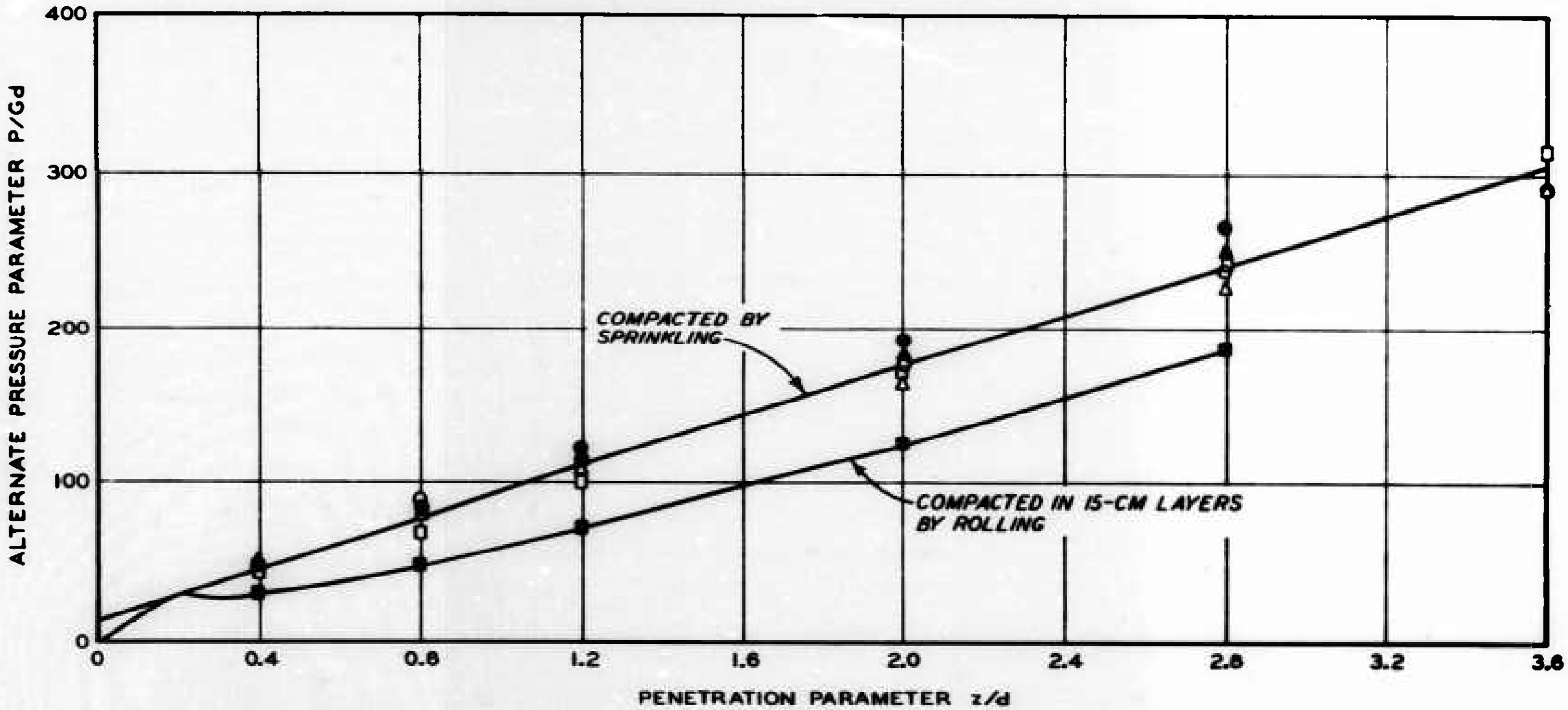
DEPENDENCE OF FRICTION ANGLE ON TEST TYPE



LEGEND

YUMA SAND	RELATIVE DENSITY, %	MORTAR SAND	RELATIVE DENSITY, %
●	20	○	34
▲	52	△	55
■	85	□	92

ADJUSTED FRICTION ANGLE
YUMA AND MORTAR SANDS

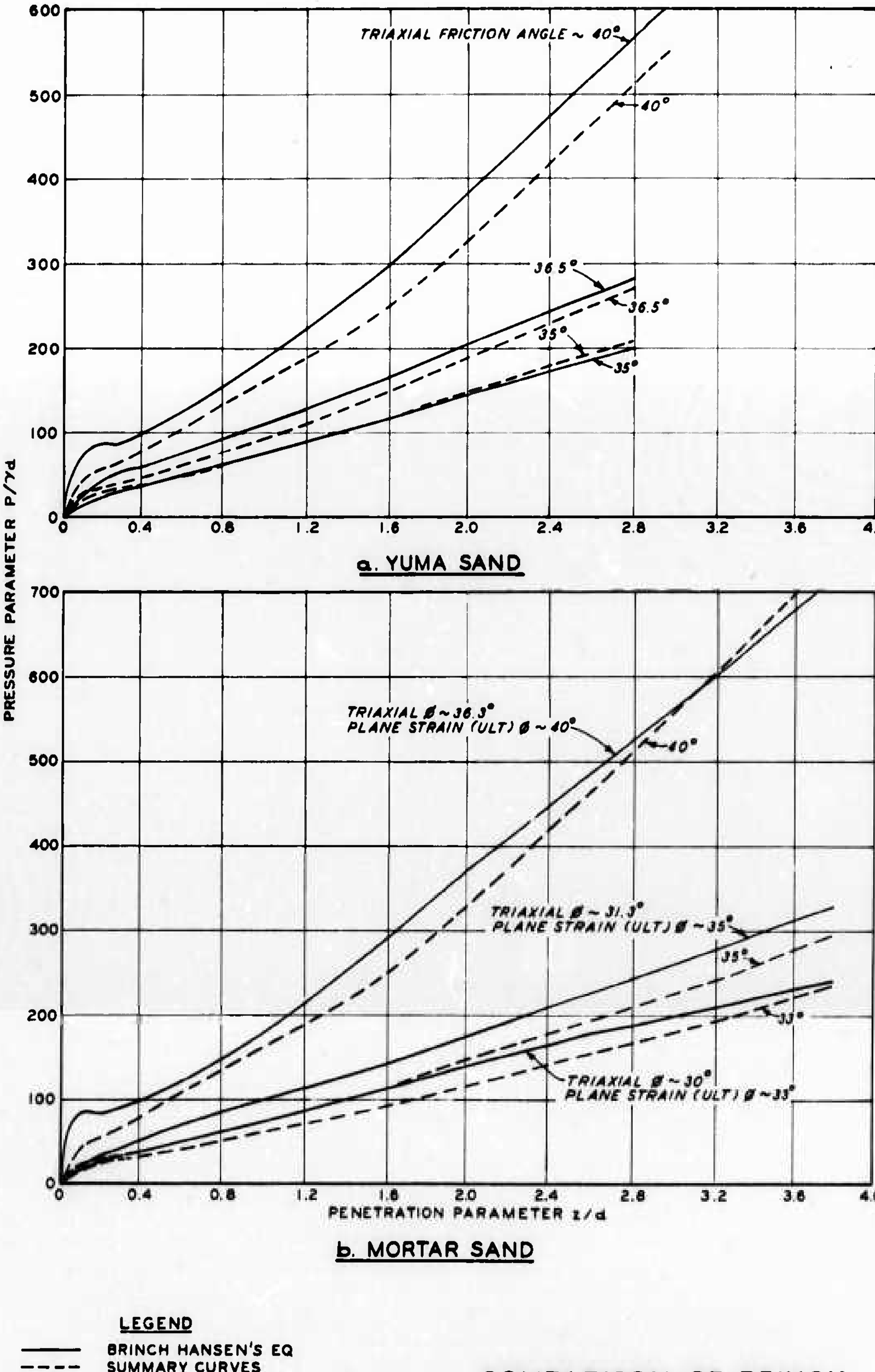


LEGEND

YUMA SAND	RELATIVE DENSITY, %	MORTAR SAND	RELATIVE DENSITY, %
●	20	○	34
▲	52	△	55
■	85	□	92

INFLUENCE OF SUBSTITUTING PENETRATION RESISTANCE GRADIENT FOR DENSITY IN PRESSURE PARAMETER

SMOOTH-WALLED CYLINDERS
YUMA AND MORTAR SANDS



COMPARISON OF BRINCH HANSEN'S COMPUTED RESULTS WITH SUMMARY CURVES

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13. ABSTRACT
The study reported herein is an analysis of the penetration of circular plates and smooth-walled and rough-walled cylinders in two sands, each prepared at three strength levels. The penetration elements ranged from 2.5 to 61 cm in diameter, and the speed of penetration in all tests was 2.5 mm/sec. No basic differences were found in the shape of the penetration resistance curves for plates and cylinders, and the forces on the base of the cylinders were only slightly higher than those on the plates. The forces due to friction on the sidewalls of the cylinders were greater for the rough-walled cylinders than for the smooth, as could be expected, but they did not vary systematically with sand density in either case. Collapse of the data into a single function for sand was achieved by plotting a dimensionless pressure parameter $P/\gamma d$ versus a penetration parameter z/d. This gave evidence that pressure-sinkage relations, and thus bearing capacity, of large footings can be predicted from model tests. Dimensionless scaling relations and theoretical equations that include a friction angle term were also found to predict bearing capacity, but the problems in measuring a true friction angle make the use of these relations questionable for this purpose. The tests were deemed successful and eliminated irregularities encountered in the results of routine tests. The data should also be of great value in investigations of depth factors for bearing capacity of sand. This report will be supplemented by a report on similar tests in clay.

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Footings						
Penetration resistance						
Sands						
Soils						

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